HIGGS PHYSICS IN THE PRECISION ERA

Fermilab joint experimental and theoretical physics seminar

4 February 2022

Gavin Salam

Rudolf Peierls Centre for Theoretical Physics &

All Souls College, University of Oxford

erc
European Research Council
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What are we trying to achieve?

the Higgs boson is the last particle of the SM.

So the SM is complete, right?

The Lagrangian and interactions: two out of three qualitatively new!

$$\mathscr{L}_{\rm SM} = \cdots + |D_\mu \phi|^2 + \psi_i y_{ij} \psi_j \phi - V(\phi)$$

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Higgs potential (→ self-interaction).

Holds the SM together.

Unobserved

Why do Yukawa couplings matter to everyone?
Because, within SM conjecture, they set quark and electron masses

$\psi_i y_{ij} \psi_j \phi$

Up quarks (mass ~ 2.2 MeV) are lighter than down quarks (mass ~ 4.7 MeV)

proton (up+up+down): 2.2 + 2.2 + 4.7 + … = 938.3 MeV
neutron (up+down+down): 2.2 + 4.7 + 4.7 + … = 939.6 MeV

So protons are **lighter** than neutrons,
→ protons are stable,
giving us hydrogen

cf. Quigg & Shrock, arXiv:0901.3958

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Bohr radius

$$a_0 = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} = \frac{\hbar}{m_e c\alpha} \propto \frac{1}{y_e}$$

electron Yukawa determines size of all atoms & energy levels of all chemical reactions

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S… …ghter …, …re stable, giving us hydrogen

We are establishing the existence of crucial new interactions

We wouldn't consider QED established if we'd only tested it to O(10%)

Boh…

$$\ldots = \frac{\ldots\epsilon_0 h^2}{m_e e^2} = \frac{\hbar}{m_e c\alpha} \propto \frac{1}{y_e}$$

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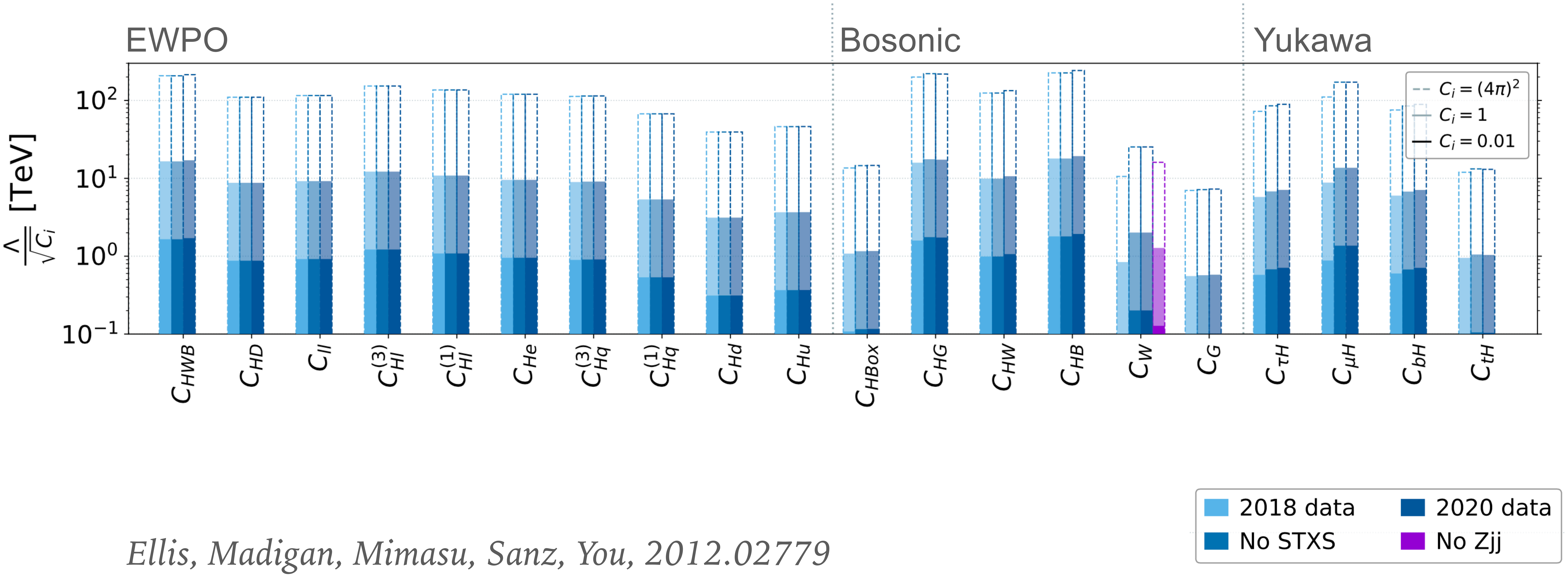
We are (indirectly) searching for new physics



Ellis, Madigan, Mimasu, Sanz, You, 2012.02779

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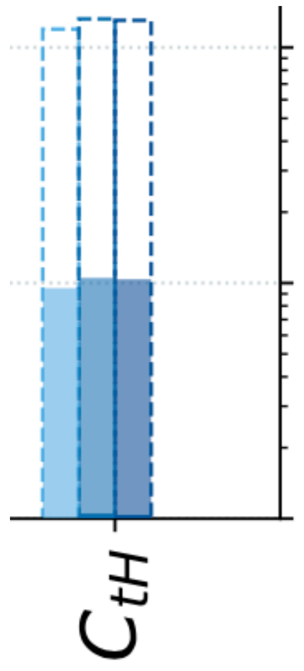

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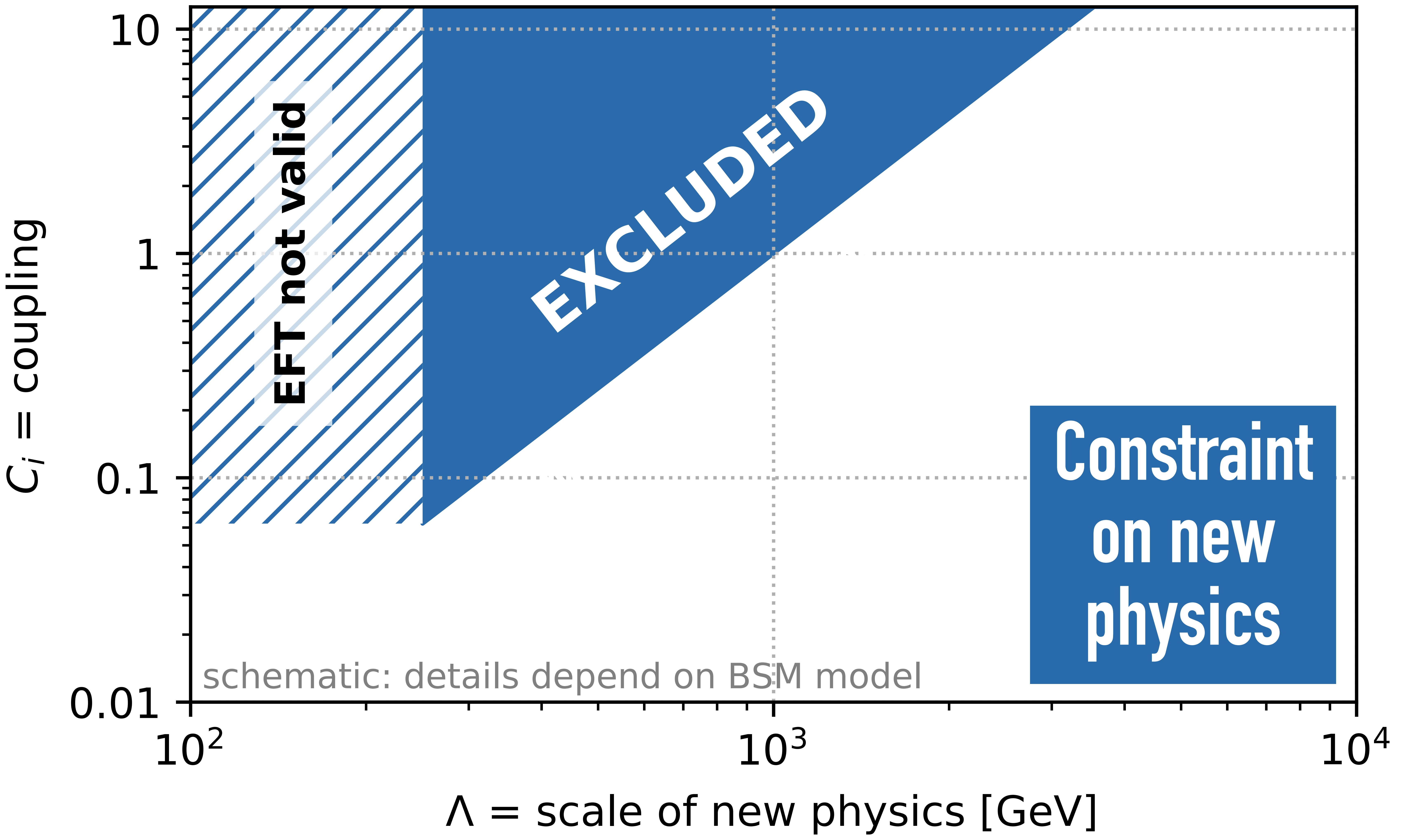

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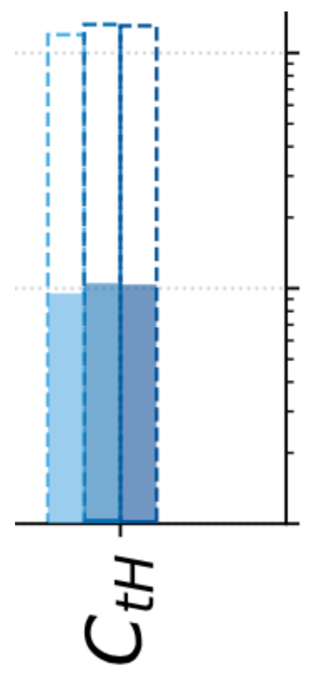

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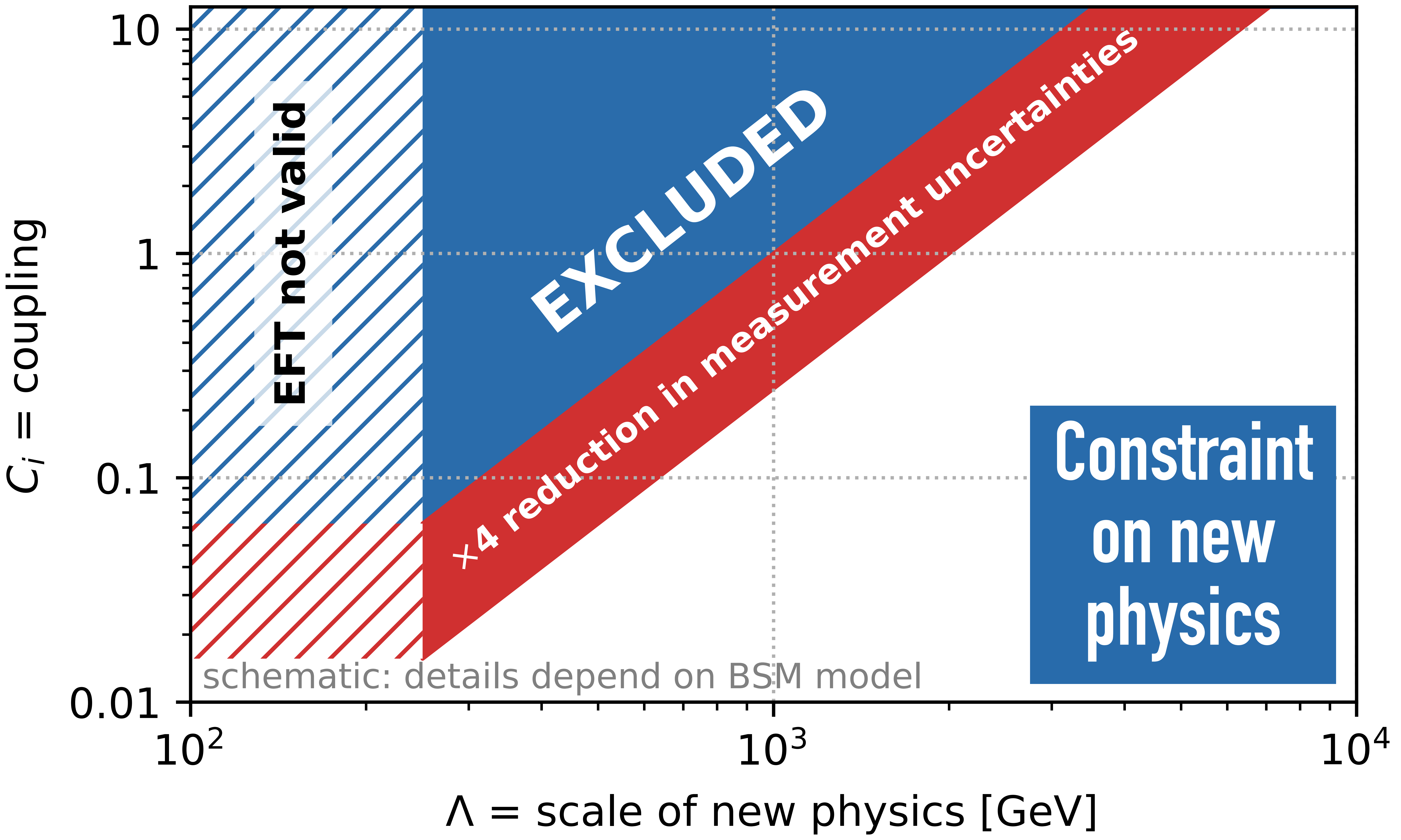

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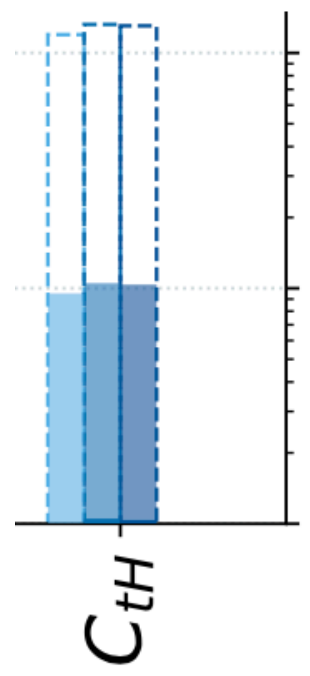
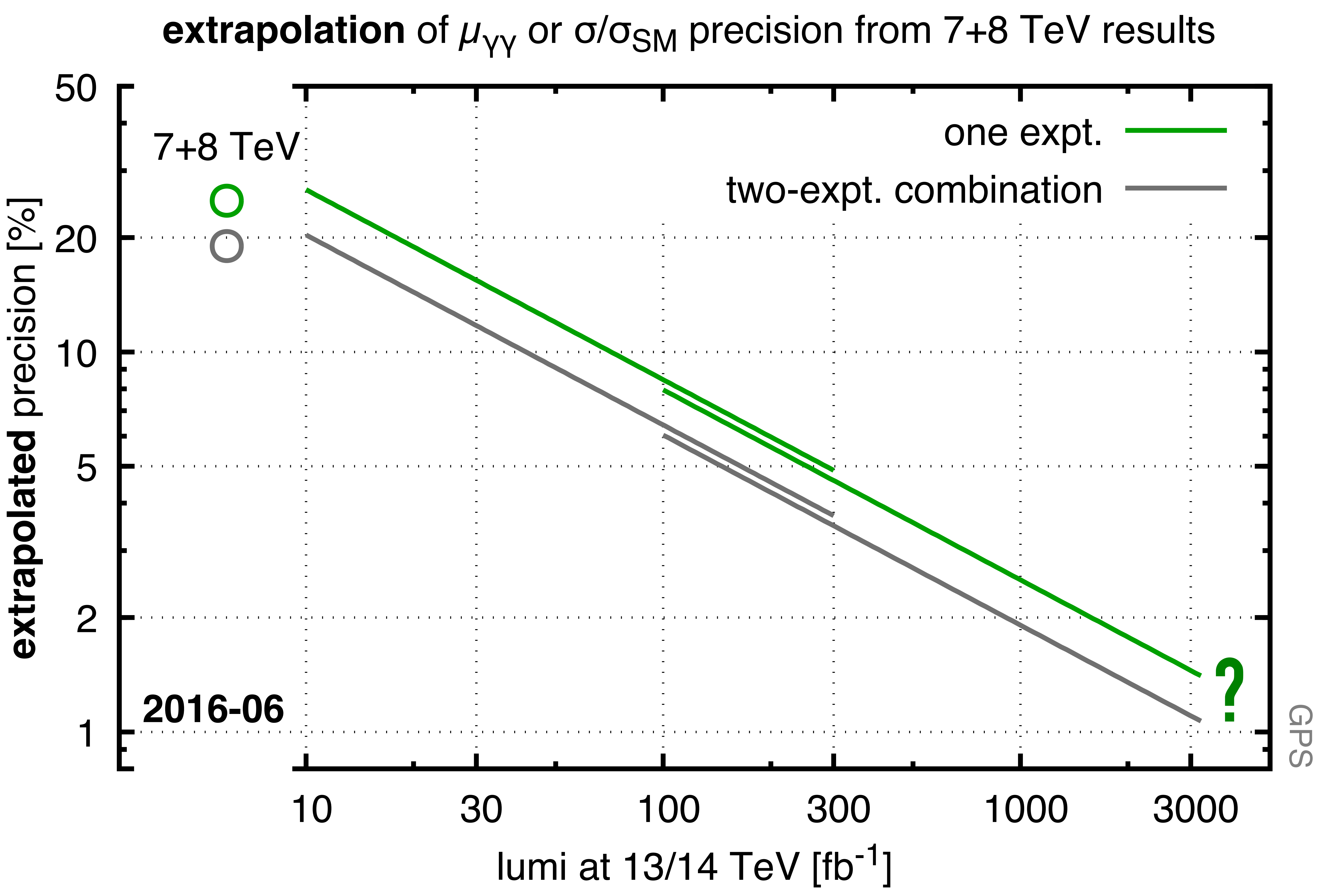


$H \to \gamma\gamma$, an indirect probe of the top Yukawa, HWW and contact ggH couplings



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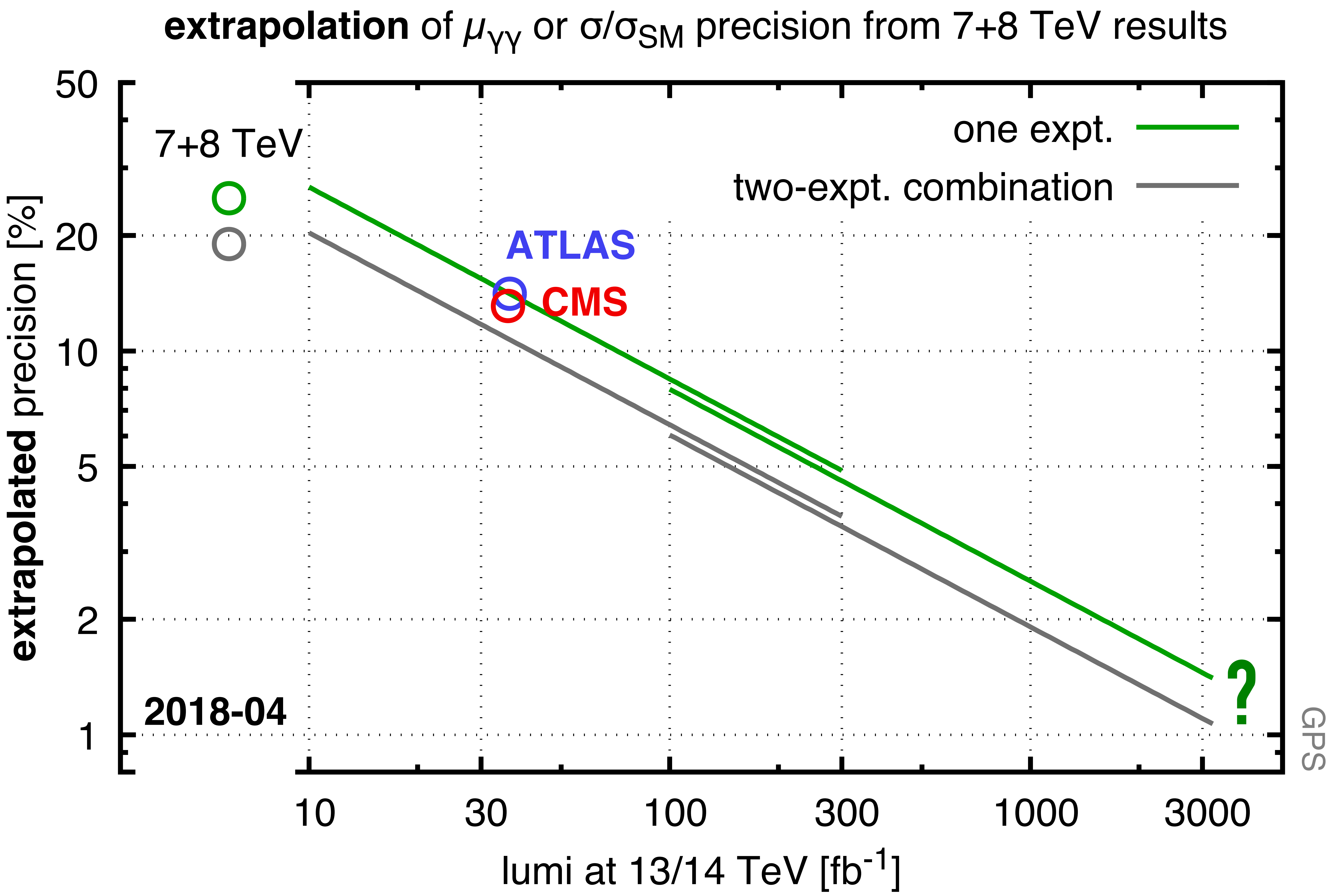

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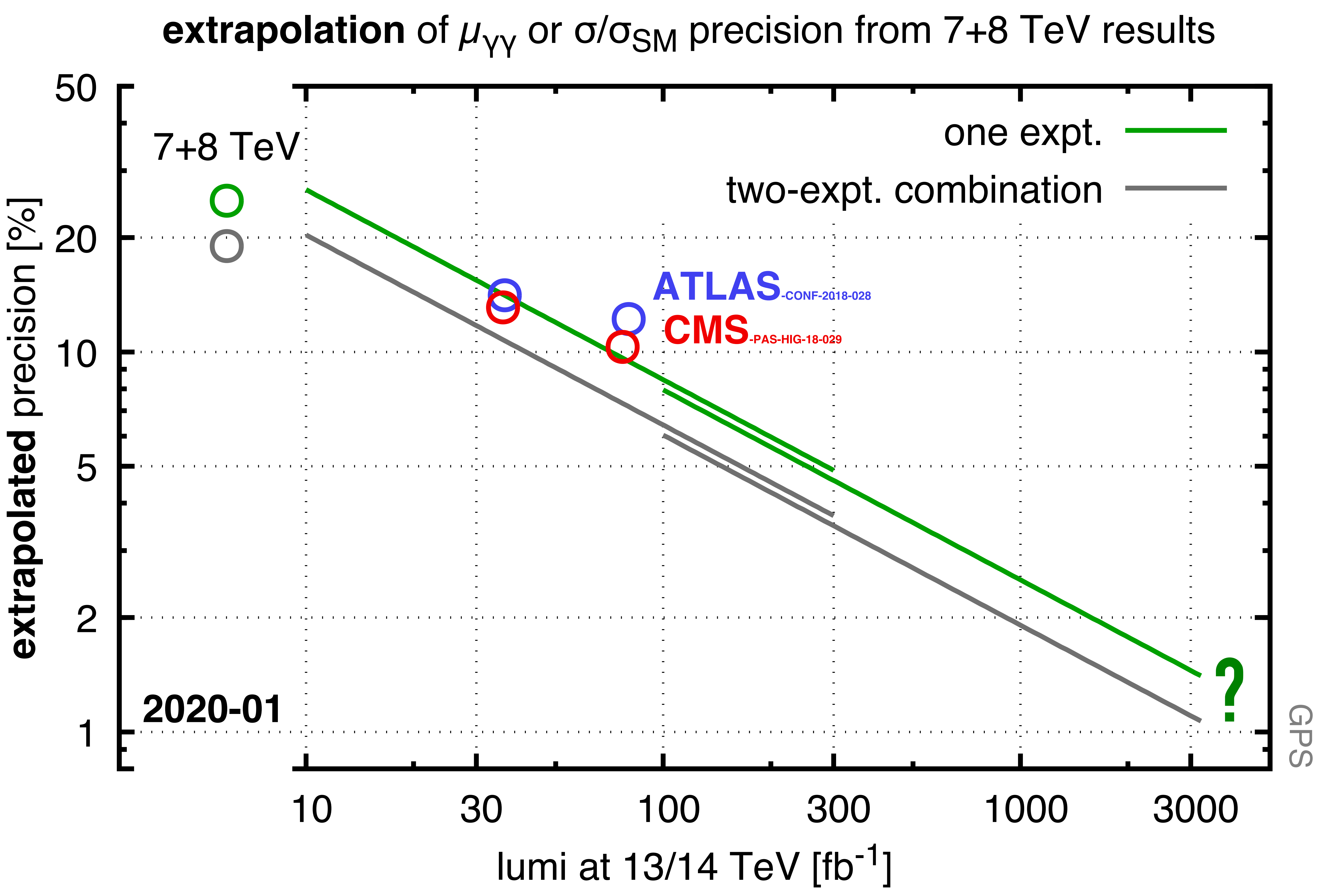

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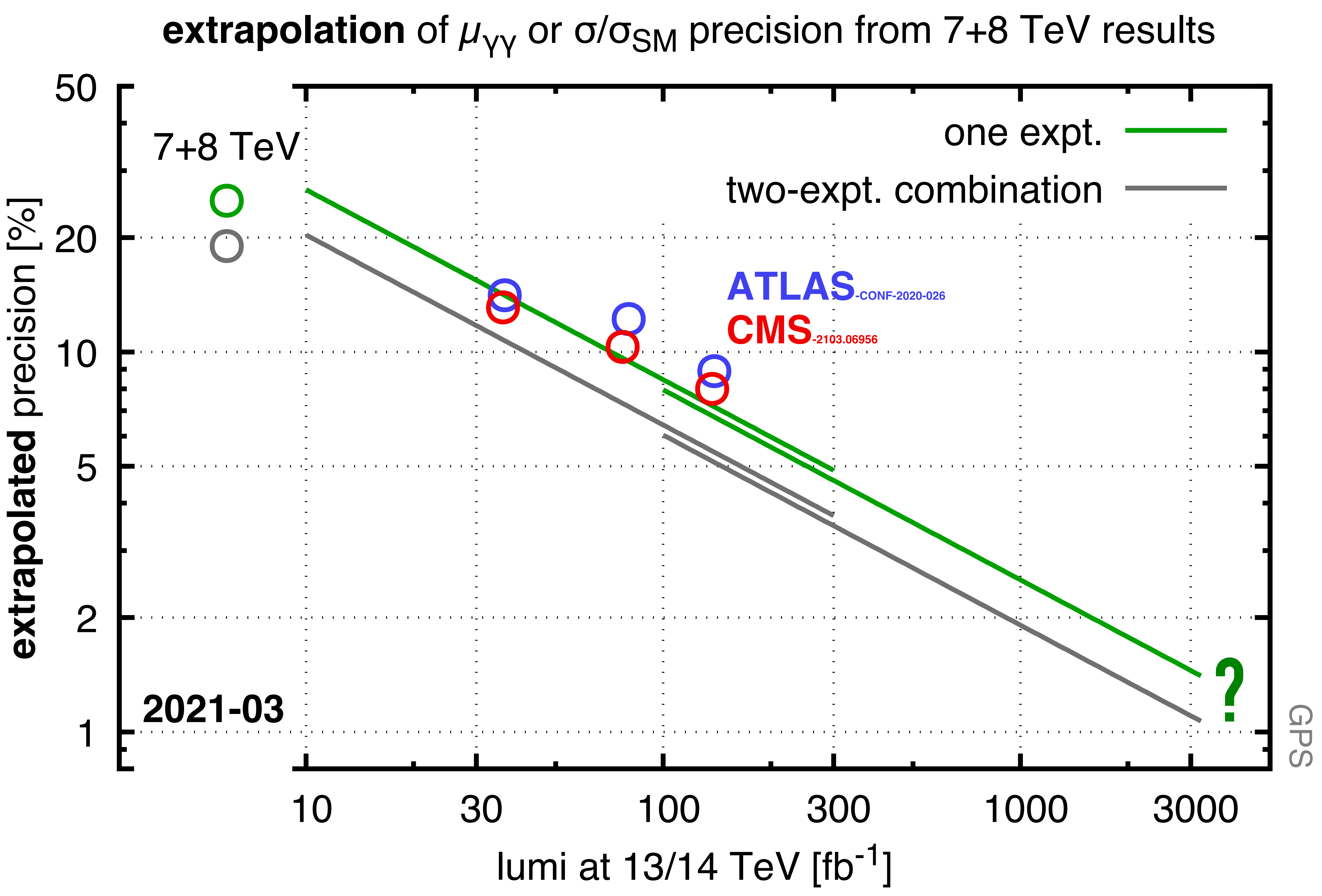

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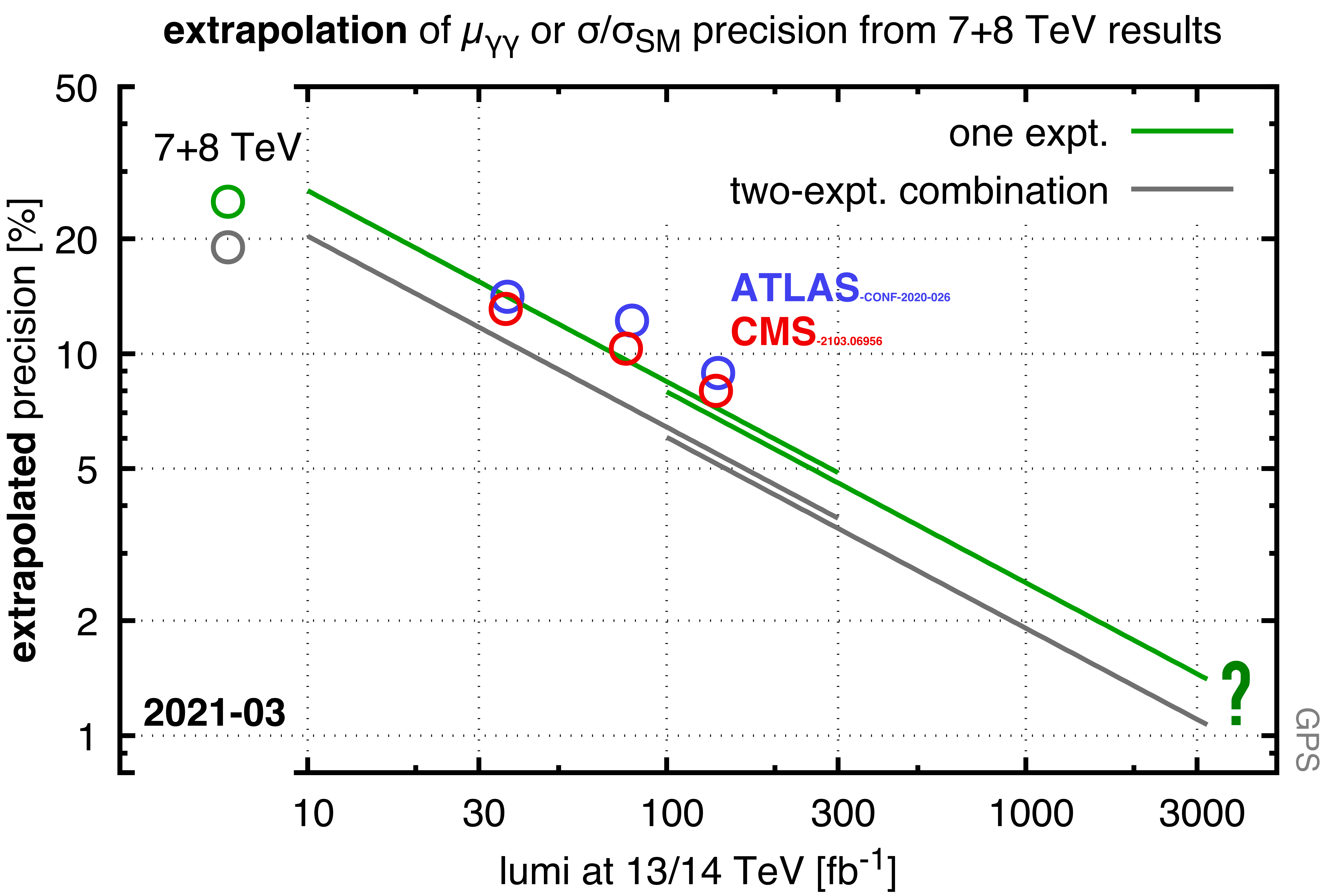


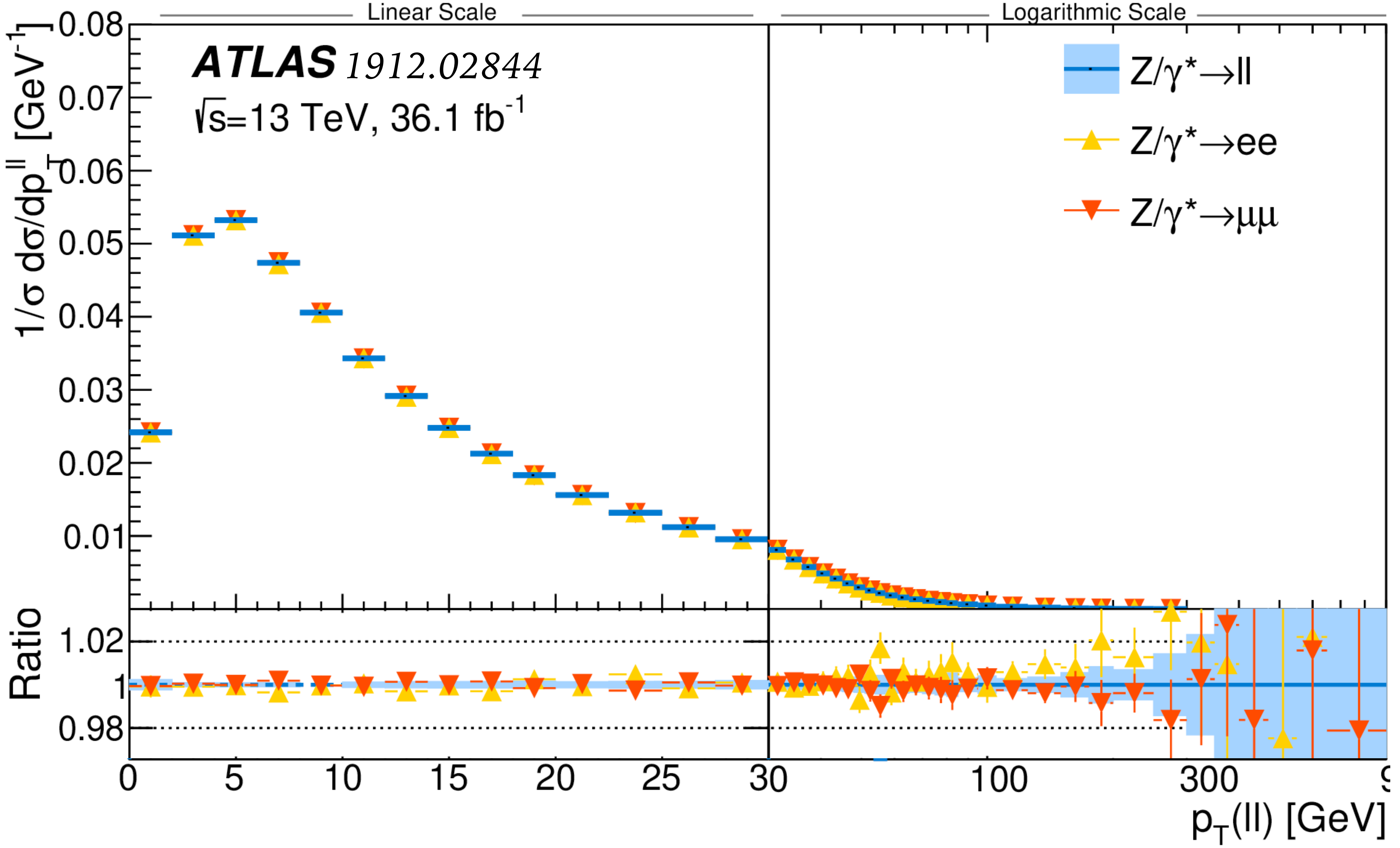
today's ATLAS and CMS total uncertainties (ratio to SM) are at the 8-9% level

5-7% stat.
3-7% syst.
~5% theo.

what is possible experimentally?

[in a quasi-ideal world]

Z p_T distribution — a showcase for LHC precision



Normalised distribution's statistical and systematic errors well below 1% all the way to $p_T \sim 200$ GeV

Largest normalisation err is luminosity then lepton ID

$$\sigma_{\text{fid}} = 736.2 \pm 0.2 \text{ (stat)} \pm 6.4 \text{ (syst)} \pm 15.5 \text{ (lumi) pb}$$

Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS

Table 4: Summary of contributions to the relative systematic uncertainty in σ_{vis} (in %) at $\sqrt{s} = 13$ TeV in 2015 and 2016. The systematic uncertainty is divided into groups affecting the description of the vdM profile and the bunch population product measurement (normalization), and the measurement of the rate in physics running conditions (integration). The fourth column indicates whether the sources of uncertainty are correlated between the two calibrations at $\sqrt{s} = 13$ TeV.

Source	2015 [%]	2016 [%]	Corr
Normalization uncertainty			
Bunch population			
Ghost and satellite charge	0.1	0.1	Yes
Beam current normalization	0.2	0.2	Yes
Beam position monitoring			
Orbit drift	0.2	0.1	No
Residual differences	0.8	0.5	Yes
Beam overlap description			
Beam-beam effects	0.5	0.5	Yes
Length scale calibration	0.2	0.3	Yes
Transverse factorizability	0.5	0.5	Yes
Result consistency			
Other variations in σ_{vis}	0.6	0.3	No
Integration uncertainty			
Out-of-time pileup corrections			
Type 1 corrections	0.3	0.3	Yes
Type 2 corrections	0.1	0.3	Yes
Detector performance			
Cross-detector stability	0.6	0.5	No
Linearity	0.5	0.3	Yes
Data acquisition			
CMS deadtime	0.5	<0.1	No
Total normalization uncertainty	1.3	1.0	—
Total integration uncertainty	1.0	0.7	—
Total uncertainty	1.6	1.2	—

Luminosity: the systematic common to all measurements

- has hovered around 2% for many years (except LHC*b*)
- CMS has recently shown that they can get it down to 1.2%
- a major achievement, because it matters across the spectrum of precision LHC results

the master formula

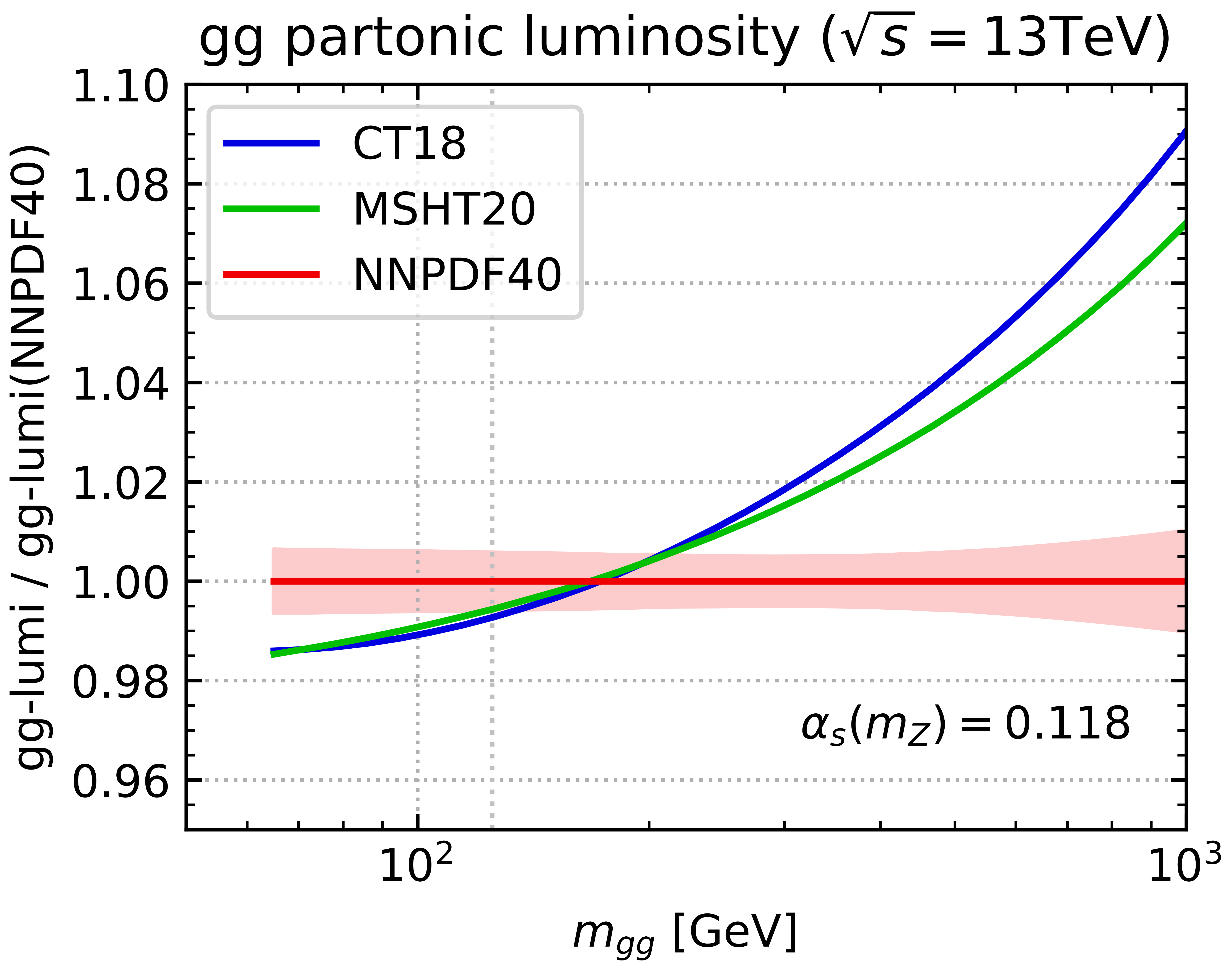
$$\sigma = \sum_{i,j} \int dx_1 dx_2\, f_{i/p}(x_1) f_{j/p}(x_2)\, \hat{\sigma}(x_1 x_2 s) \times \left[1 + \mathcal{O}(\Lambda/M)^p\right]$$

HXSWG YR 4 gg→H uncertainties

m_H (GeV)	Cross Section (pb)	TH Gaussian %	±PDF %	$\pm\alpha_s$ %
125.00	4.858E+01	±3.9	±1.9	±2.6

$$\sigma = \sum_{i,j} \int dx_1 dx_2 f_{i/p}(x_1) f_{j/p}(x_2) \hat{\sigma}(x_1 x_2 s) \times \left[1 + \mathcal{O}(\Lambda/M)^p\right]$$

Comparing modern PDF sets



NB: PDF4LHC21 will use CT18/MSHT20/NNPDF31

gg-lumi, ratio to PDF4LHC15 @ m_H

PDF4LHC15	1.0000	±	0.0184
CT18	0.9914	±	0.0180
MSHT20	0.9930	±	0.0108
NNPDF40	0.9986	±	0.0058

$\times 3$

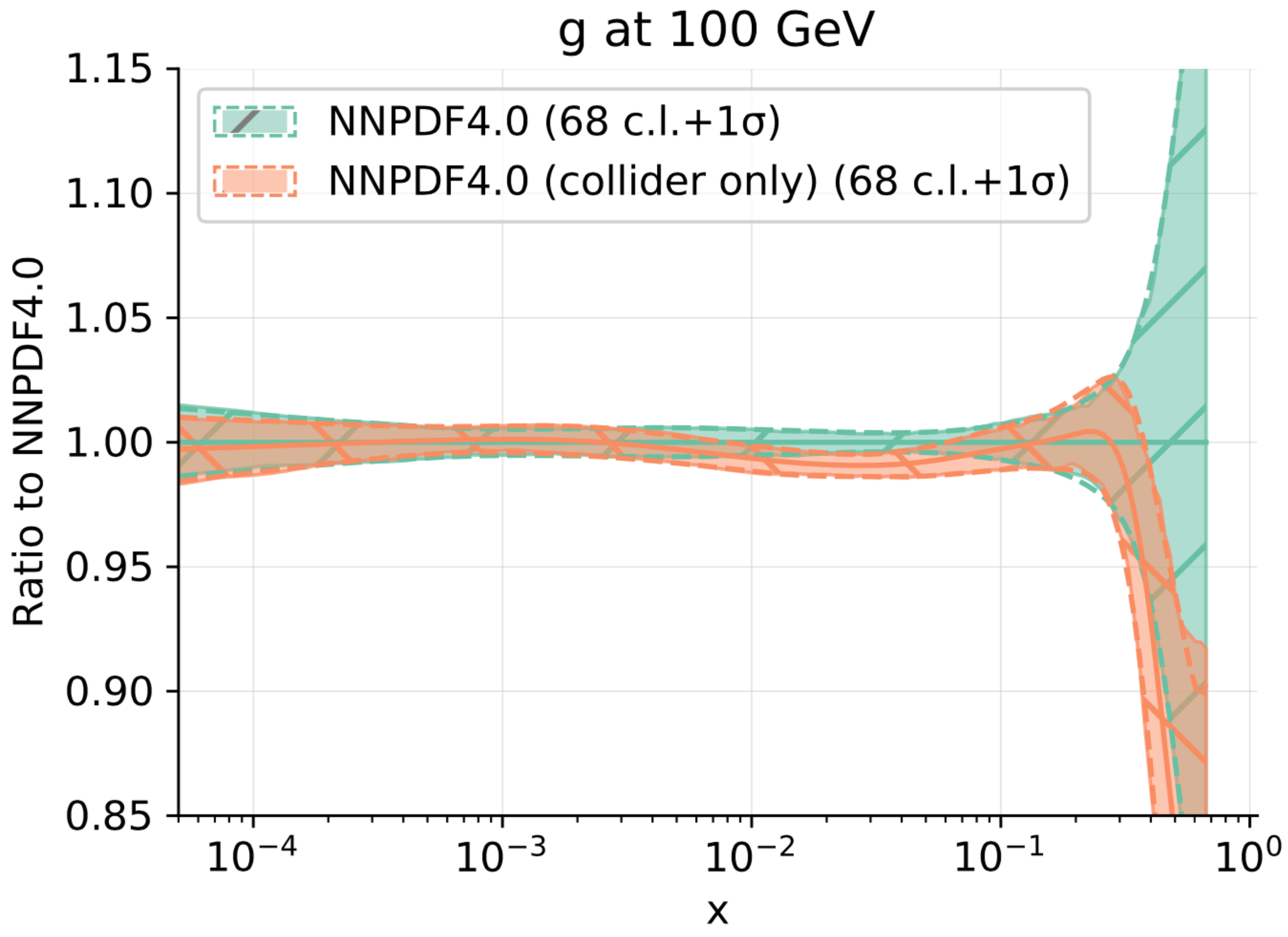
Amazing that MSHT20 & NNPDF40 are reaching %-level precision

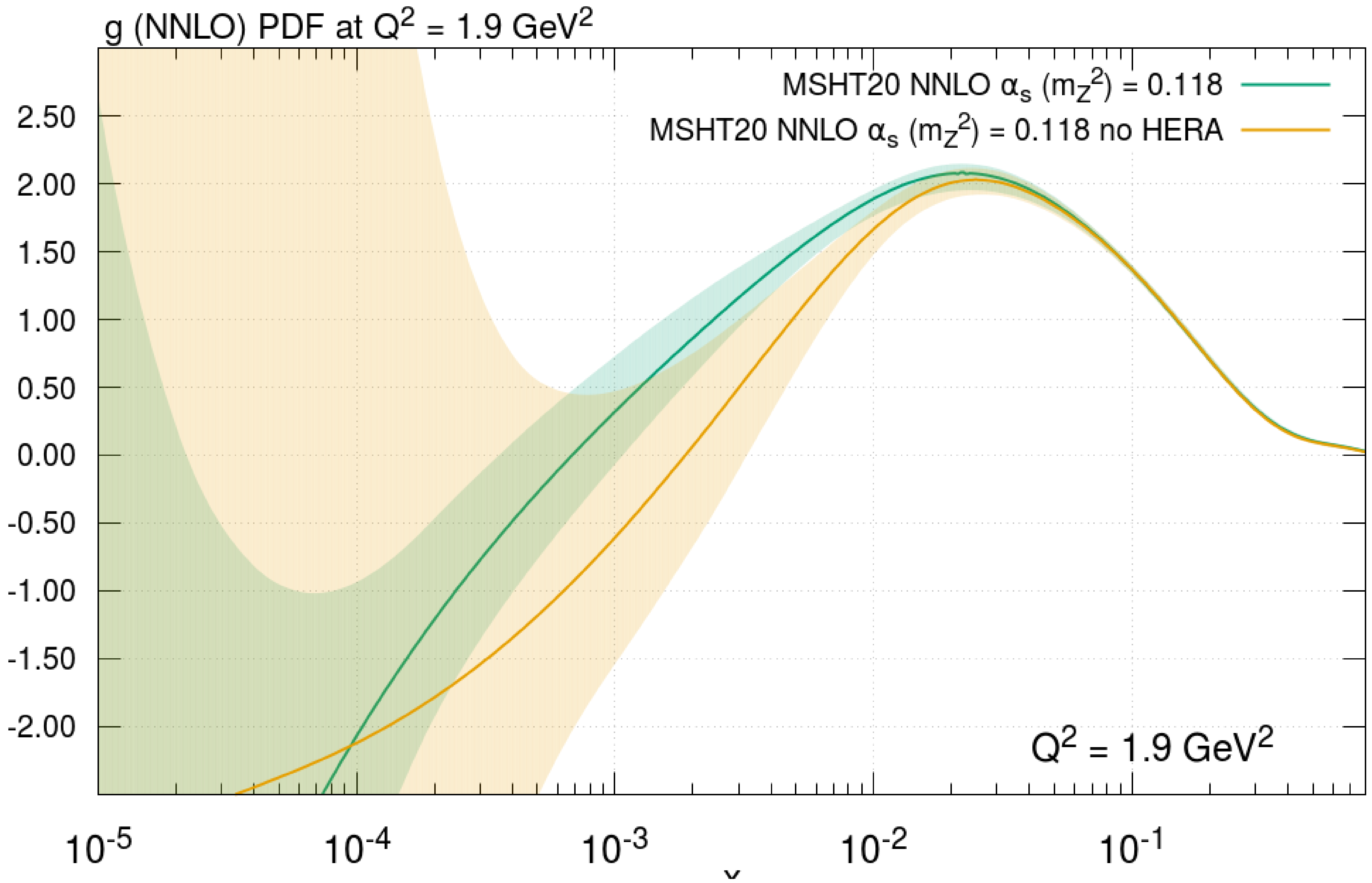
Differences include

- methodology (replicas & NN fits, tolerance factors, etc.)
- data inputs
- treatment of charm

At this level, QED effects probably no longer optional

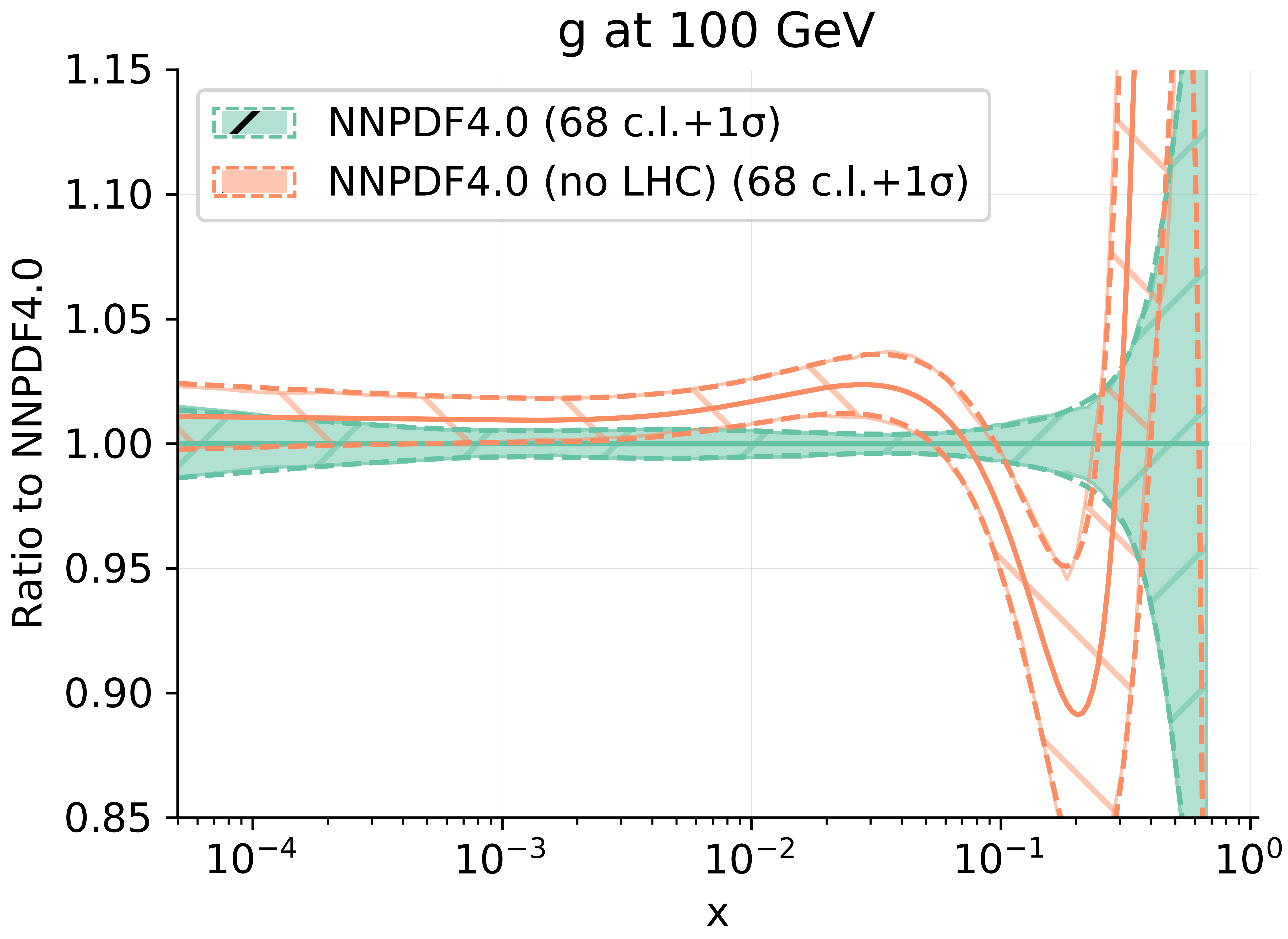
Removing DIS data (and associated worries about sizeable Λ^2/Q^2 corrections)





Reassuring indications that results are not (substantially) affected by Λ^2/Q^2 corrections from low-Q^2 DIS part of fit

Removing LHC data



- LHC data appears to be dominant in constraining the gluon
- One clear question is how to interpret gg-lumi uncertainties $\lesssim 1\,\%$ when all input cross sections at hadron colliders have larger theory uncertainties.

HXSWG YR 4 gg→H uncertainties

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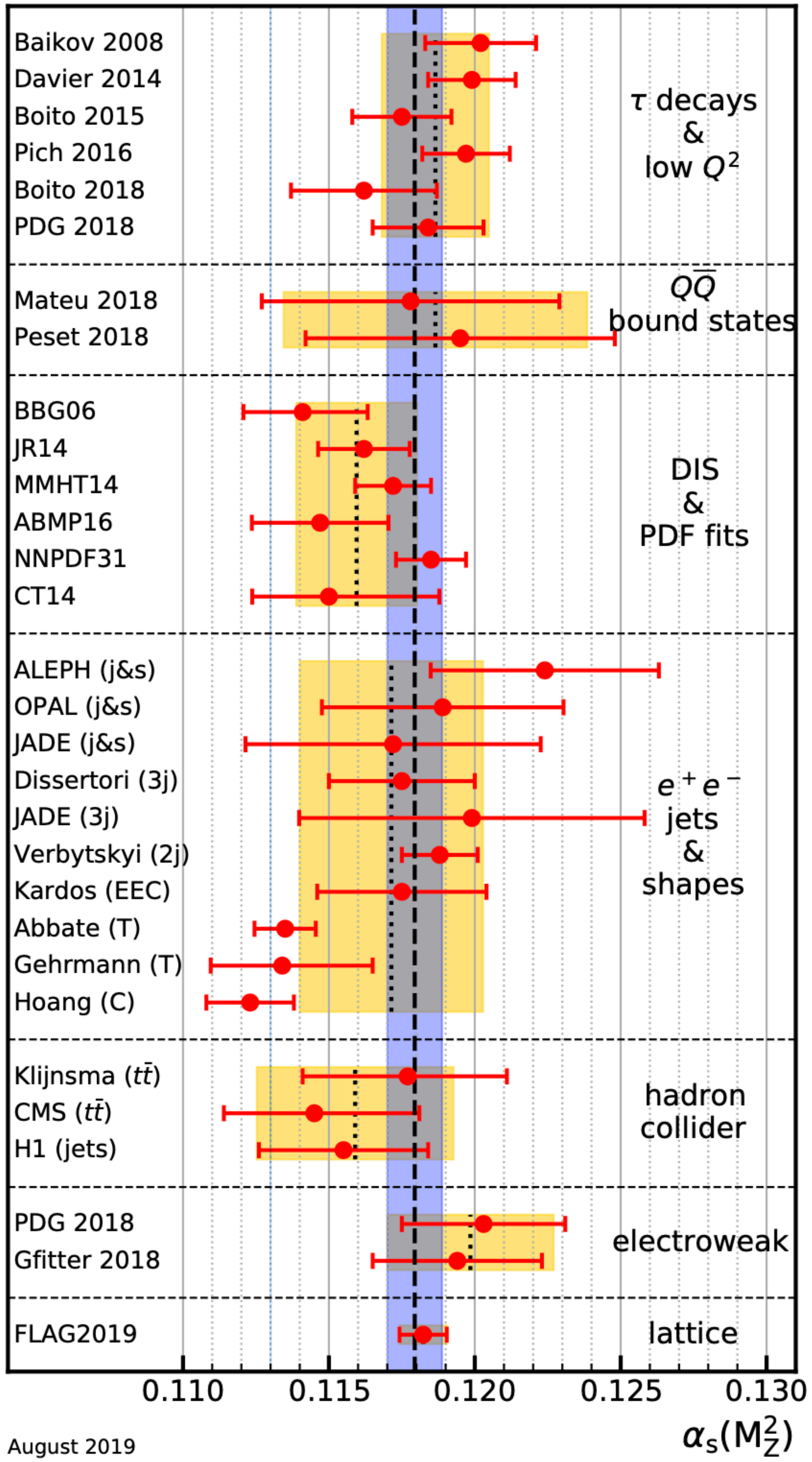


The strong coupling

HXSWG YR4	0.1180 ± 0.0015
PDG 2019	0.1179 ± 0.0010
ALPHA lattice (step scaling)	0.1185 ± 0.0008

Impact of ±0.0010 on $\sigma_{gg\to H}$ is ±2.1% (NNPDF40+ihixs)

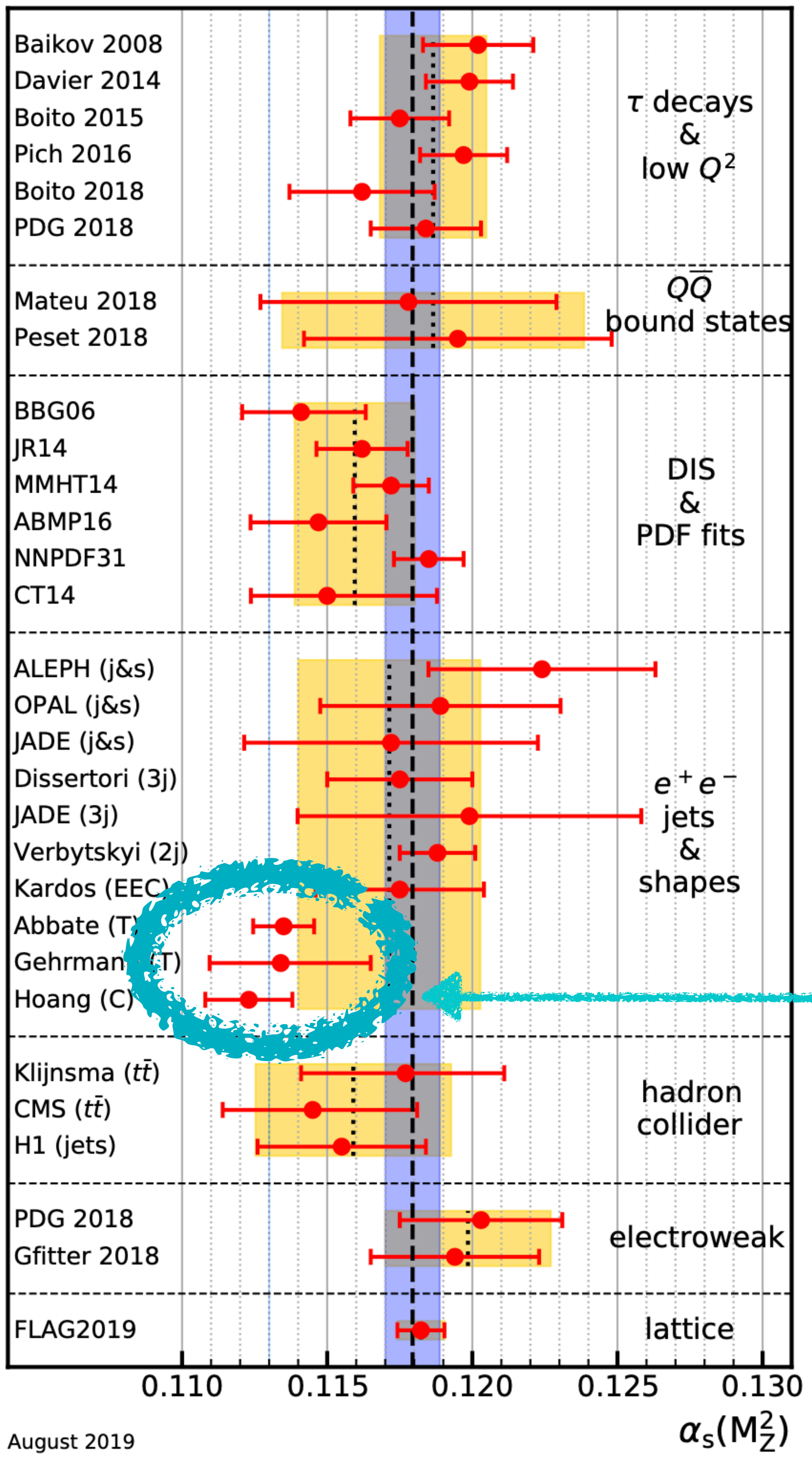
Until we get FCC-ee Z hadronic width measurement, I don't see any way forward that isn't (step scaling) lattice-based

Lattice determinations of the strong coupling

2101.04762

Luigi Del Debbio[a], Alberto Ramos[b,1]

The strong coupling



HXSWG YR4	0.1180 ± 0.0015
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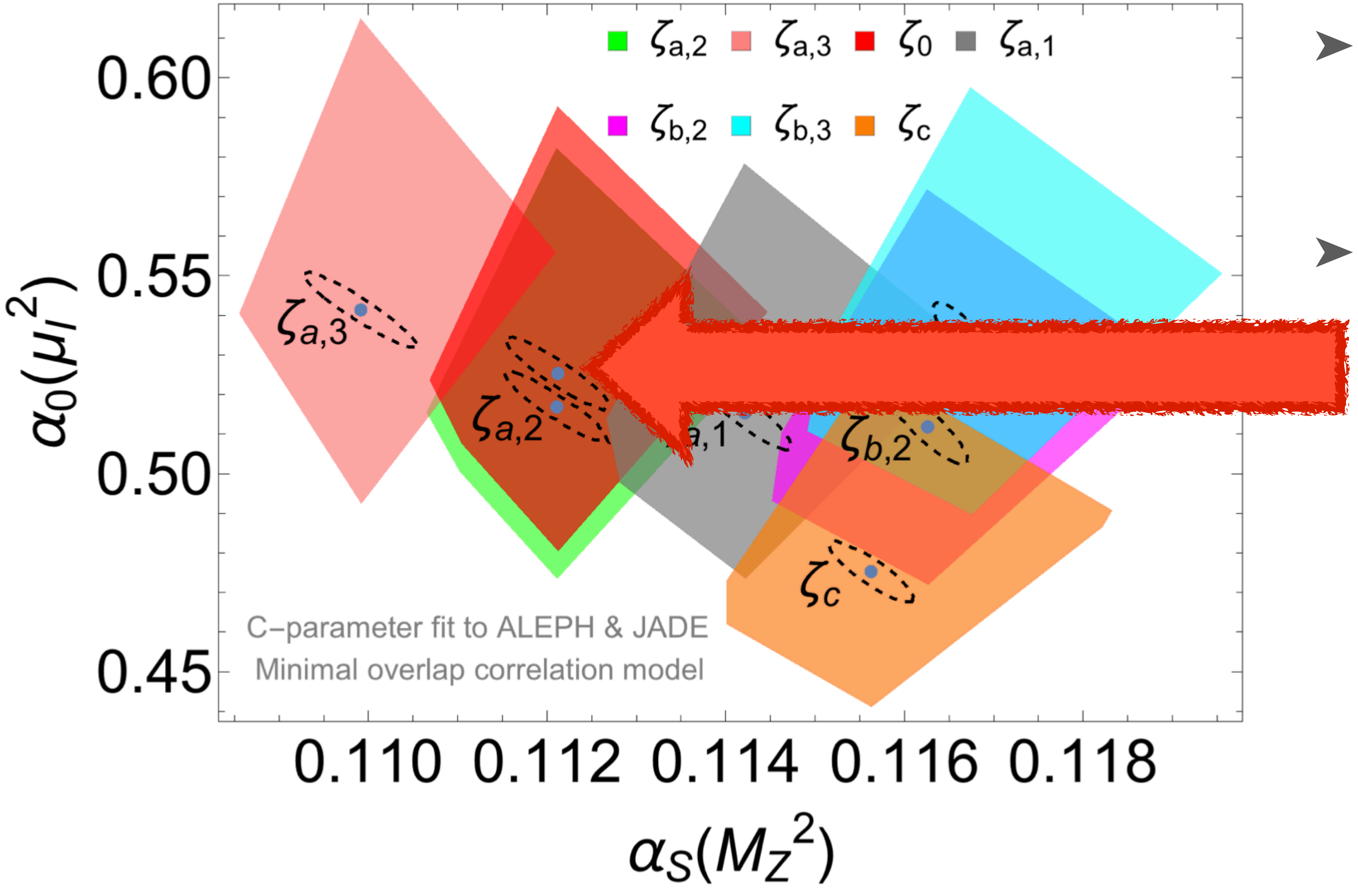
ALPHA lattice (step scaling)	0.1185 ± 0.0008
e^+e^- C-parameter [SCET]	0.1123 ± 0.0015
e^+e^- Thrust [SCET]	0.1135 ± 0.0011

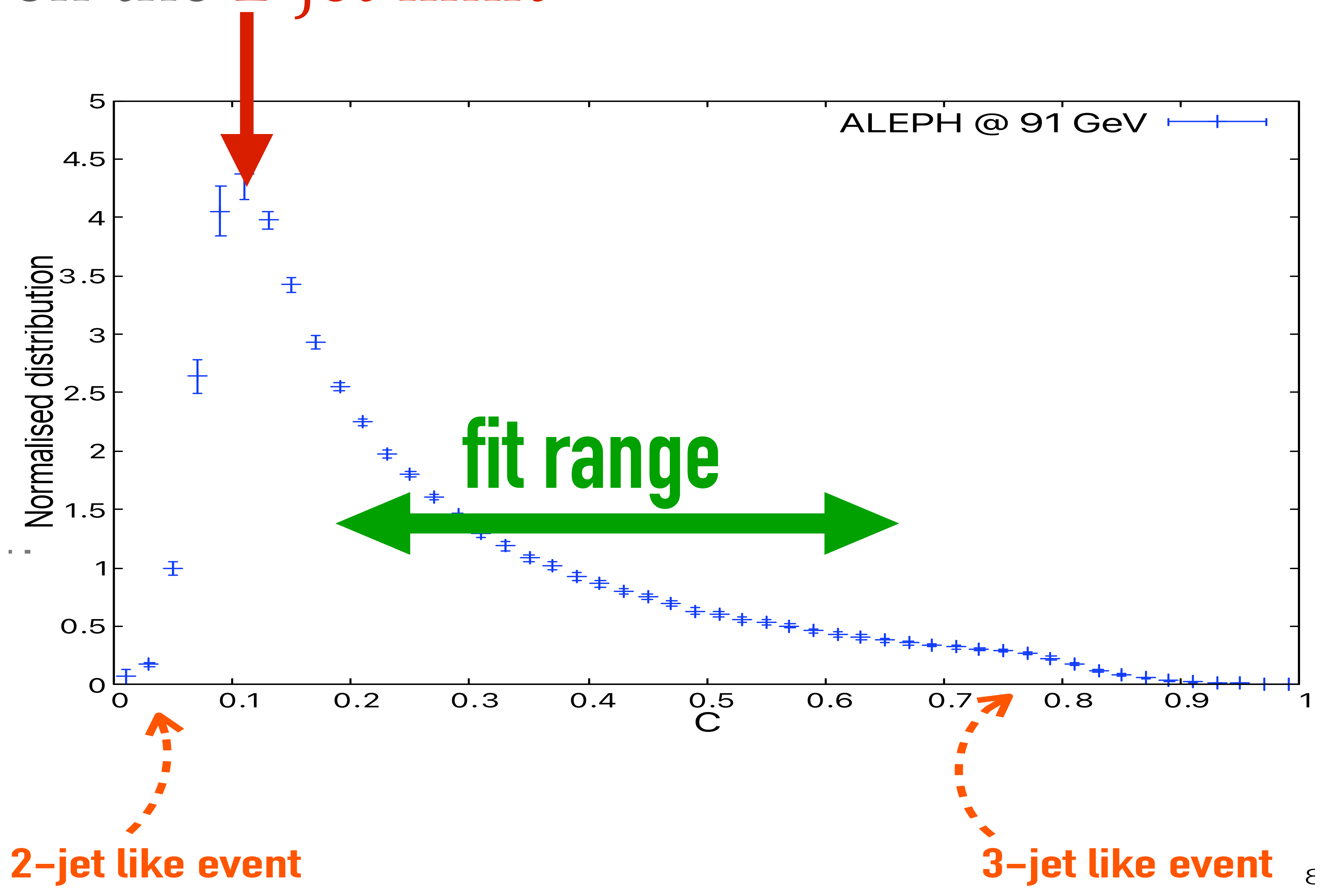
Aside from EW fit and ALPHA lattice, most determinations depend, in some way or other, on measurements that are uncomfortably close / sensitive to non-perturbative physics, cf. terms $(\Lambda/Q)^p$, where $\Lambda \sim \Lambda_{\mathrm{QCD}} \sim 1\,\mathrm{GeV}$

C-param fits with different assumptions for Λ/Q correction (between 2 & 3-jet limits)



Luisoni, Monni & GPS, 2012.00622

- measurement essentially looks at rate of 3rd jet emission in $e^+e^- \to q\bar{q}$
- 0.1123 ± 0.0015 ↔ *assumption* about the structure of Λ/Q corrections, based on the 2-jet limit



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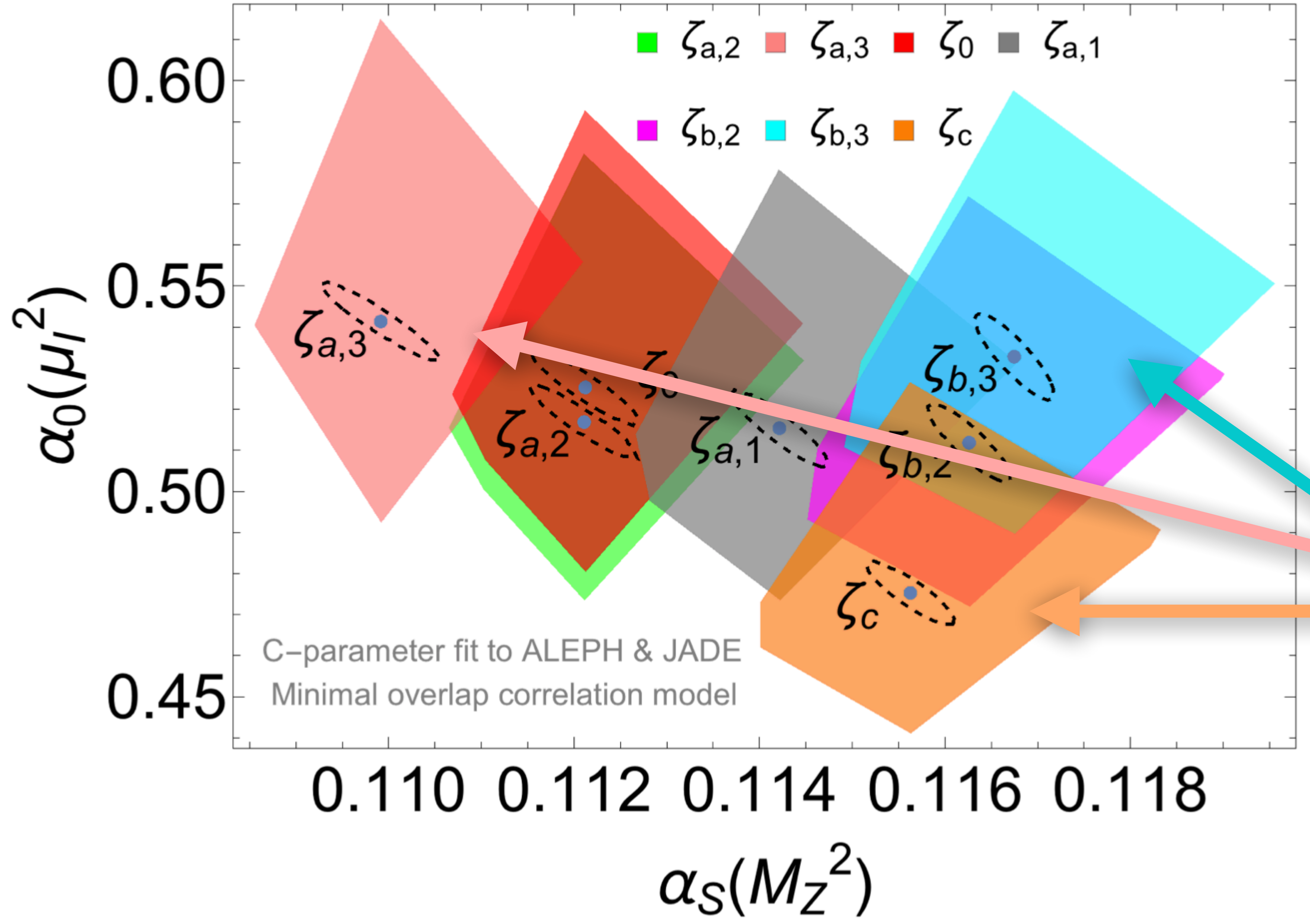

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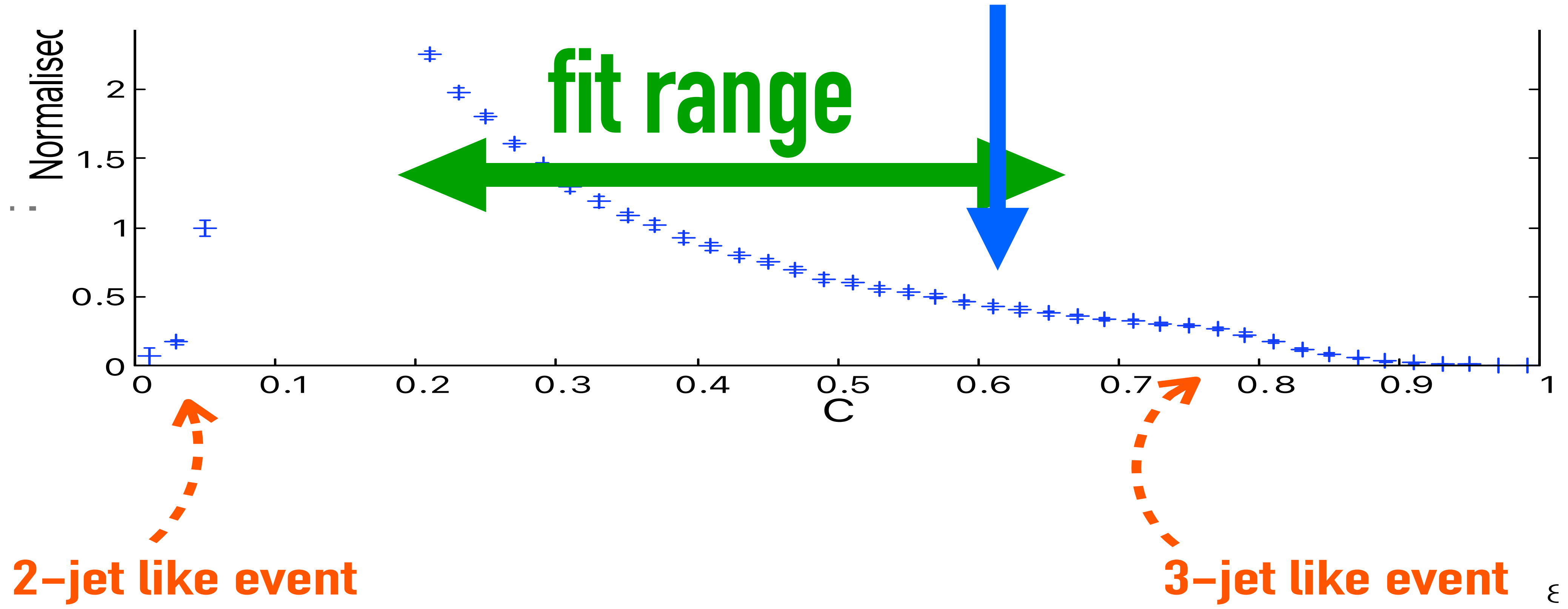

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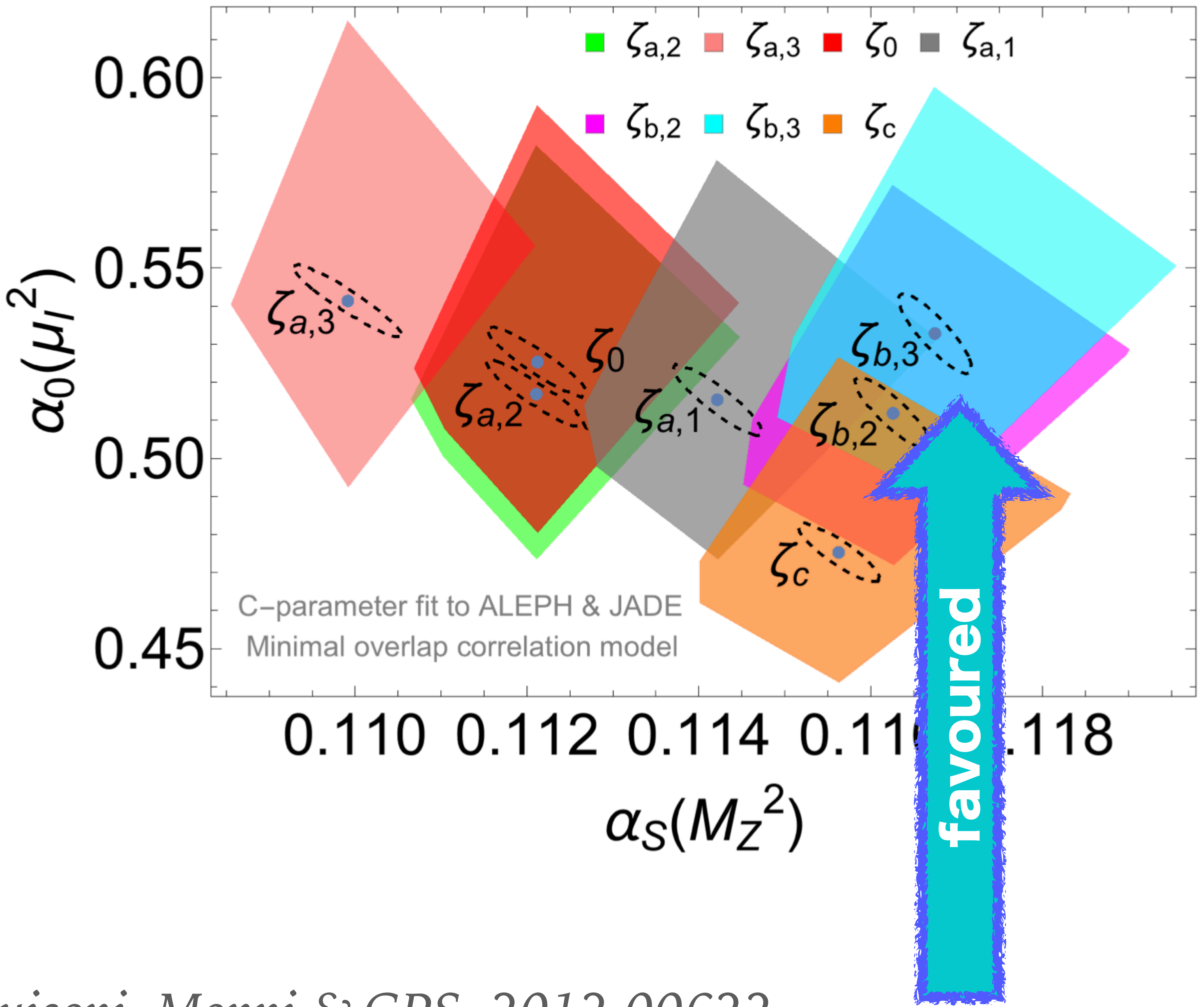

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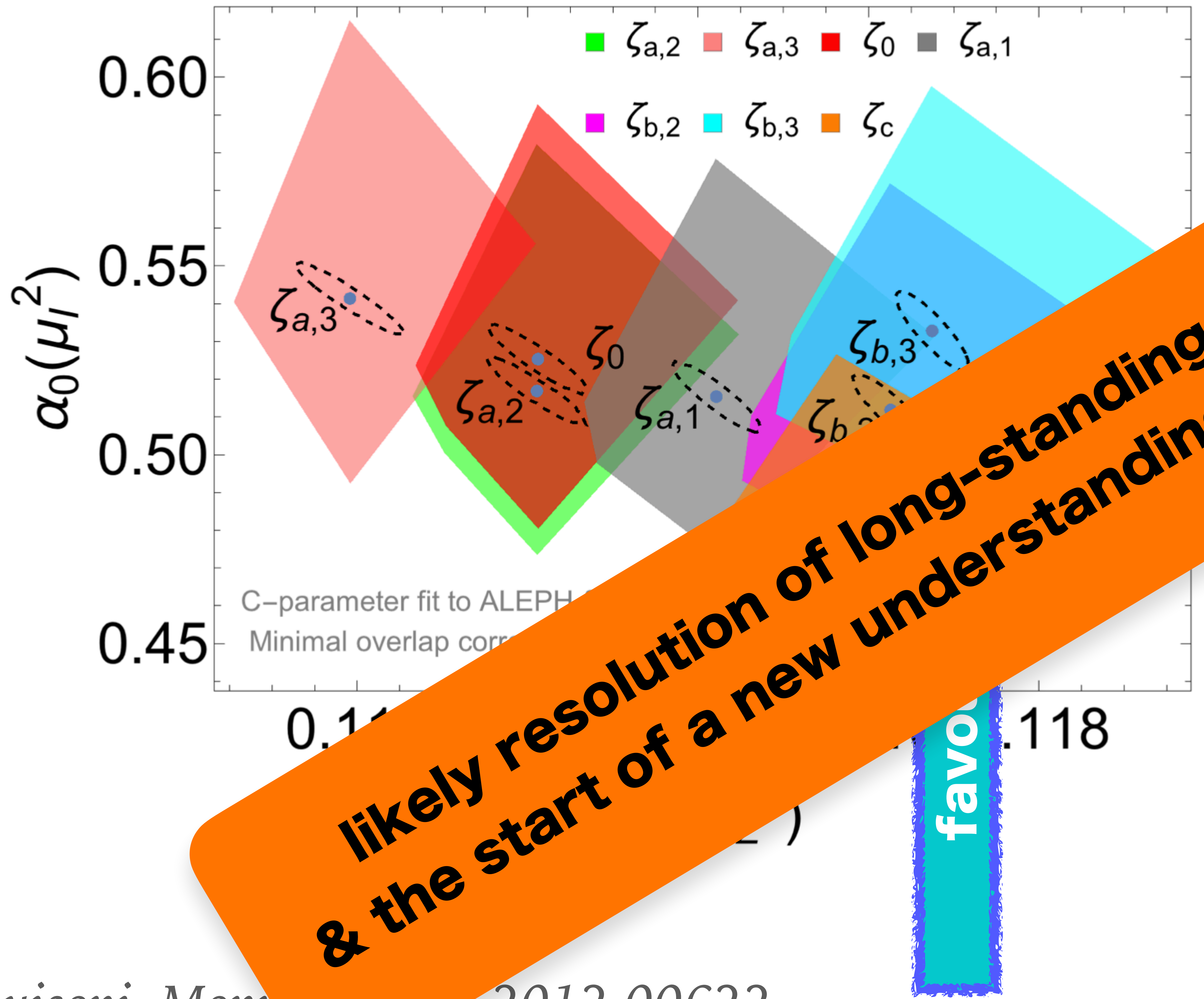
Luisoni, Monni & GPS, 2012.00622

Caola, Ferrario Ravasio, Limatola, Melnikov & Nason, 2108.08897

C-param fits with different assumptions for Λ/Q correction (between 2 & 3-jet limits)



likely resolution of long-standing 4σ discrepancy & the start of a new understanding of Λ/Q corrections

- measu… …ntially looks at rate of 3-… $e^+e^- \to q\bar{q}$
- …s ↔ *assumption* about …ure of Λ/Q corrections, based …e 2-jet limit
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Luisoni, Monn…, 2012.00622

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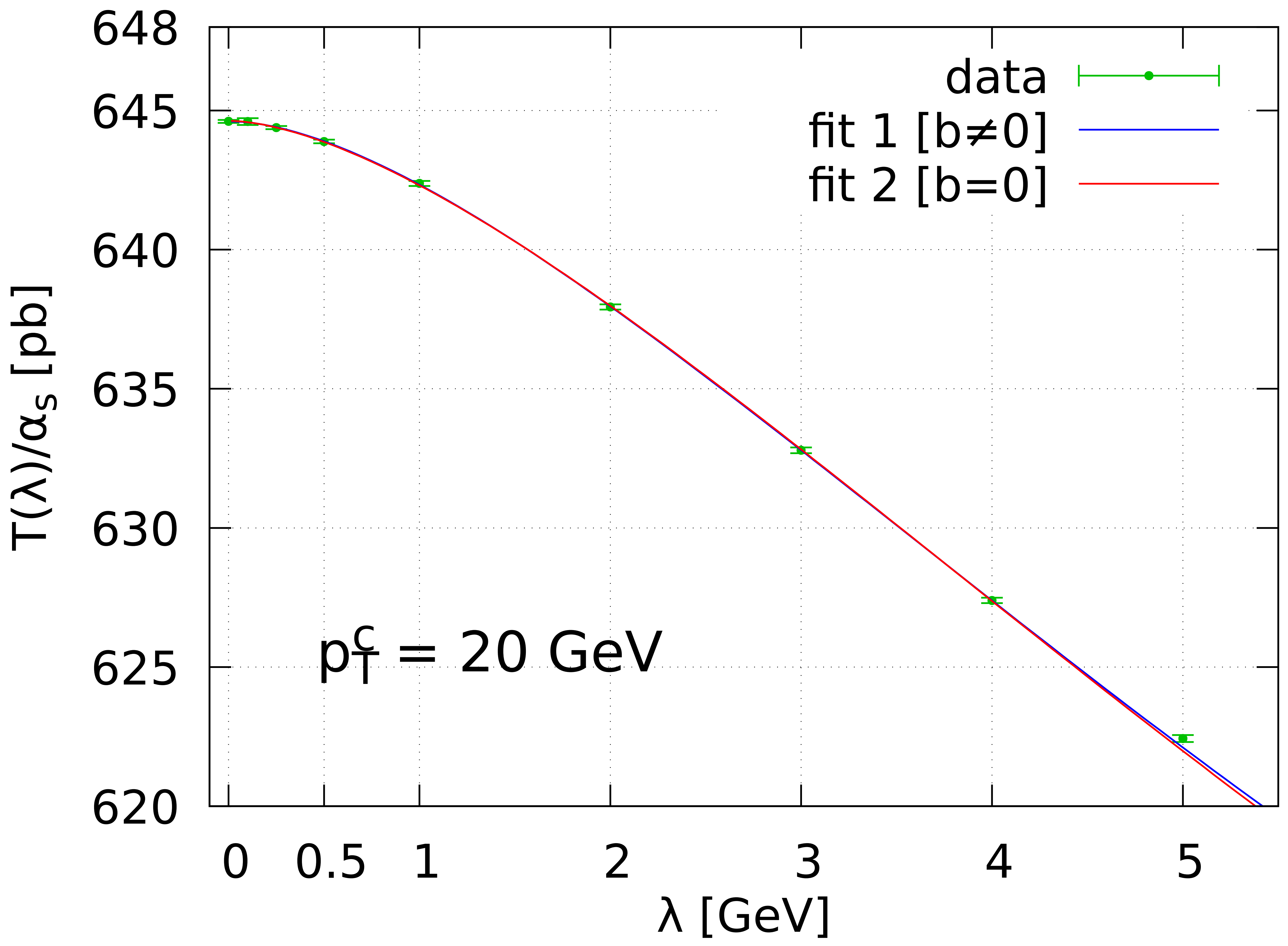
the non-perturbative part at hadron colliders

$$\sigma = \sum_{i,j} \int dx_1 dx_2\, f_{i/p}(x_1) f_{j/p}(x_2)\, \hat{\sigma}(x_1 x_2 s) \times \left[1 + \mathcal{O}(\Lambda/M)^p\right]$$

What is value of p in $(\Lambda/Q)^p$?

- LEP event-shape (C-parameter, thrust) fit troubles came about because $p = 1$
  $\Lambda \sim 0.5\,\text{GeV} \to (\Lambda/20\text{GeV}) \sim 2.5\,\%$
- Jet physics at LHC is dirty because $p = 1$ (hadronisation & MPI)
- Hadron-collider inclusive and rapidity-differential Drell-Yan cross sections are believed to have $p = 2$ (Higgs hopefully also), so leptonic / photonic decays should be clean, aside from isolation.
  $\Lambda \sim 0.5\,\text{GeV} \to (\Lambda/125\text{GeV})^2 \sim 0.002\,\%$
  [Beneke & Braun, hep-ph/9506452; Dasgupta, hep-ph/9911391]
- But at LHC, we're also interested in Z, W and Higgs production with non-zero p_T
  Nobody knew if we have $(\Lambda/p_T)^p$ with $p = 1$ (a disaster) or $p = 2$ (all is fine)

What is value of p in $(\Lambda/Q)^p$?



- Explicit calculations with an effective gluon mass (λ) can provide a strong indication
- Flatness in plot for $\lambda \to 0$ indicates **absence of $p = 1$** (linear) contribution
- arguably the most important result of the past 18 months, because it lays foundations for precision physics at non-zero p_T

Ferraro Ravasio, Limatola & Nason, 2011.14114

+ analytic demonstration in Caola, Ferrario Ravasio, Limatola, Melnikov & Nason, 2108.08897

the perturbative part

m_H (GeV)	Cross Section (pb)	TH Gaussian %	±PDF %	$\pm\alpha_s$ %
125.00	4.858E+01	±3.9	±1.9	±2.6

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Standard QCD+EW perturbation theory, plus a conceptual surprise

Gluon Fusion — The Error Budget

[adapted from Alexander Huss @ Higgs 2021 see his slides for much more discussion]

[Czakon, Harlander, Klappert, Niggetiedt '20]

Remove one source of uncertainty!

Future:

- light-quark mass effects
  - large logs to resum?

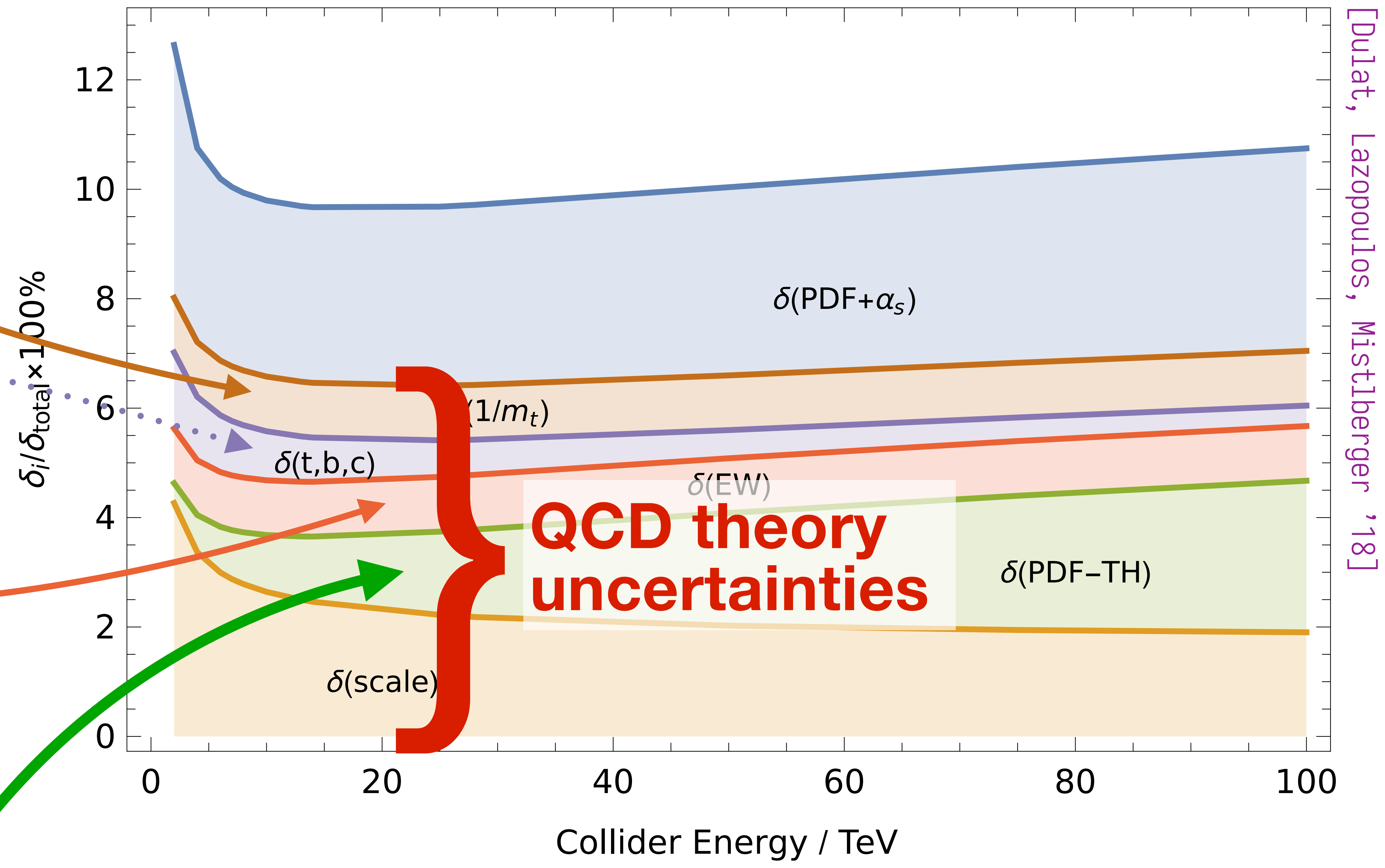
[Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer '20]

Reduce uncertainty: $\sim 1\,\% \to 0.6\,\%$

Future:

- quark-induced EW contributions
- large p_T^H?
- m_t dependence in QCD amplitude?

Sources of Uncertainties:



- $\delta(\text{PDF} + \alpha_s)$ — more data & accurate determinations
- $\delta(\text{PDF} - \text{TH})$ — missing N3LO PDFs (AP kernels)

4-loop splitting (low moments): Moch, Rujil, Ueda, Vermaseren & Vogt '21
Drell-Yan @ N3LO: Duhr, Dulat & Mistlberger, '20, '21
still to be incorporated into PDF fits

Previous slide was for Higgs ("inclusive") total cross section
Starting point for any hadron-collider analysis: acceptance (fiducial) cuts

E.g. ATLAS/CMS $H \to \gamma\gamma$ cuts

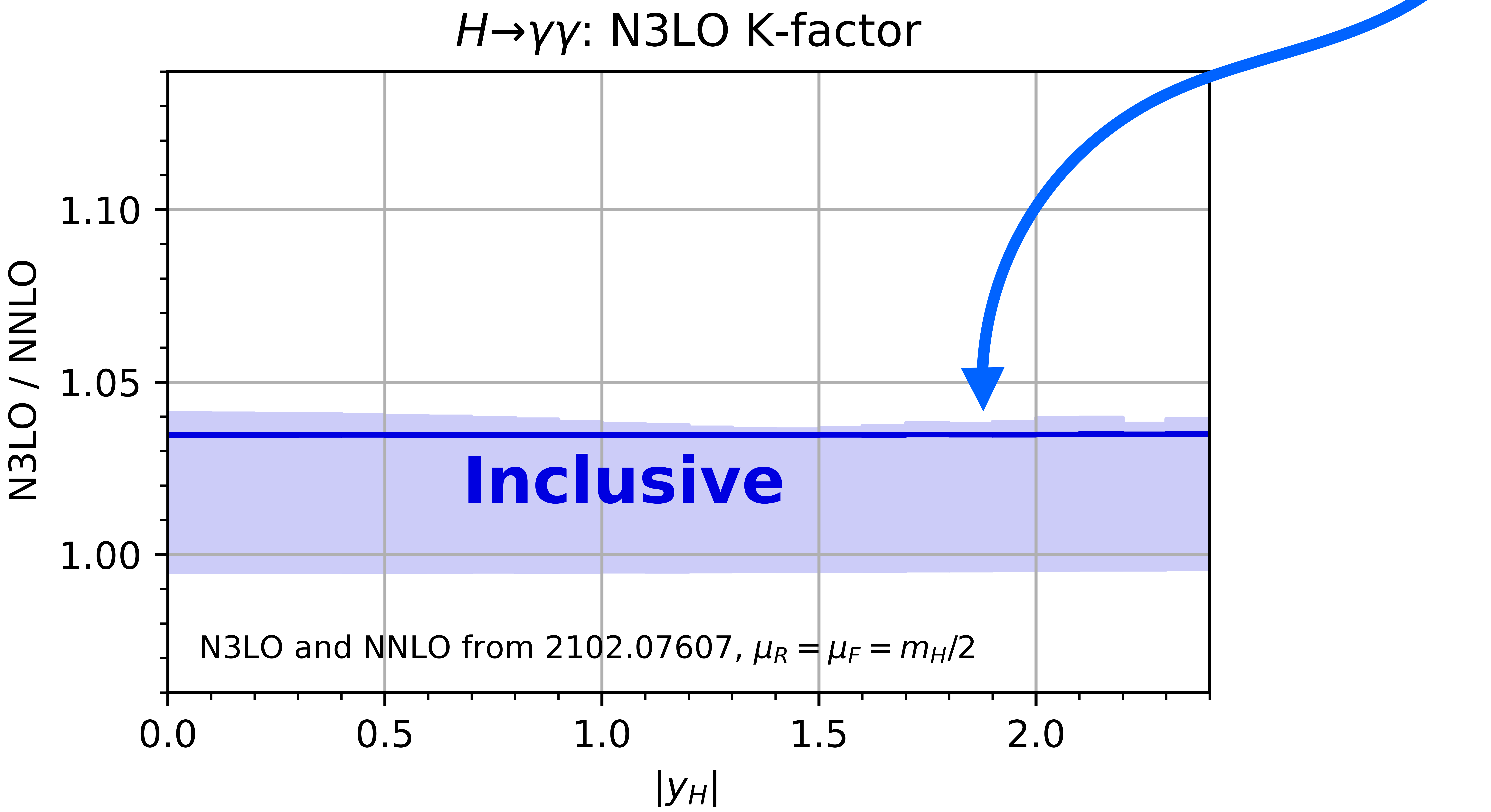
- Higher-p_t photon: $p_{t,\gamma} > 0.35 m_{\gamma\gamma}$ (ATLAS) or $m_{\gamma\gamma}/3$ (CMS)
- Lower-p_t photon: $p_{t,\gamma} > 0.25 m_{\gamma\gamma}$
- Both photons: additional rapidity and isolation cuts

Essential for good reconstruction of the photons and for rejecting large low-p_t backgrounds.

Theory-experiment comparisons with identical "fiducial" cuts often considered the Gold Standard of collider physics

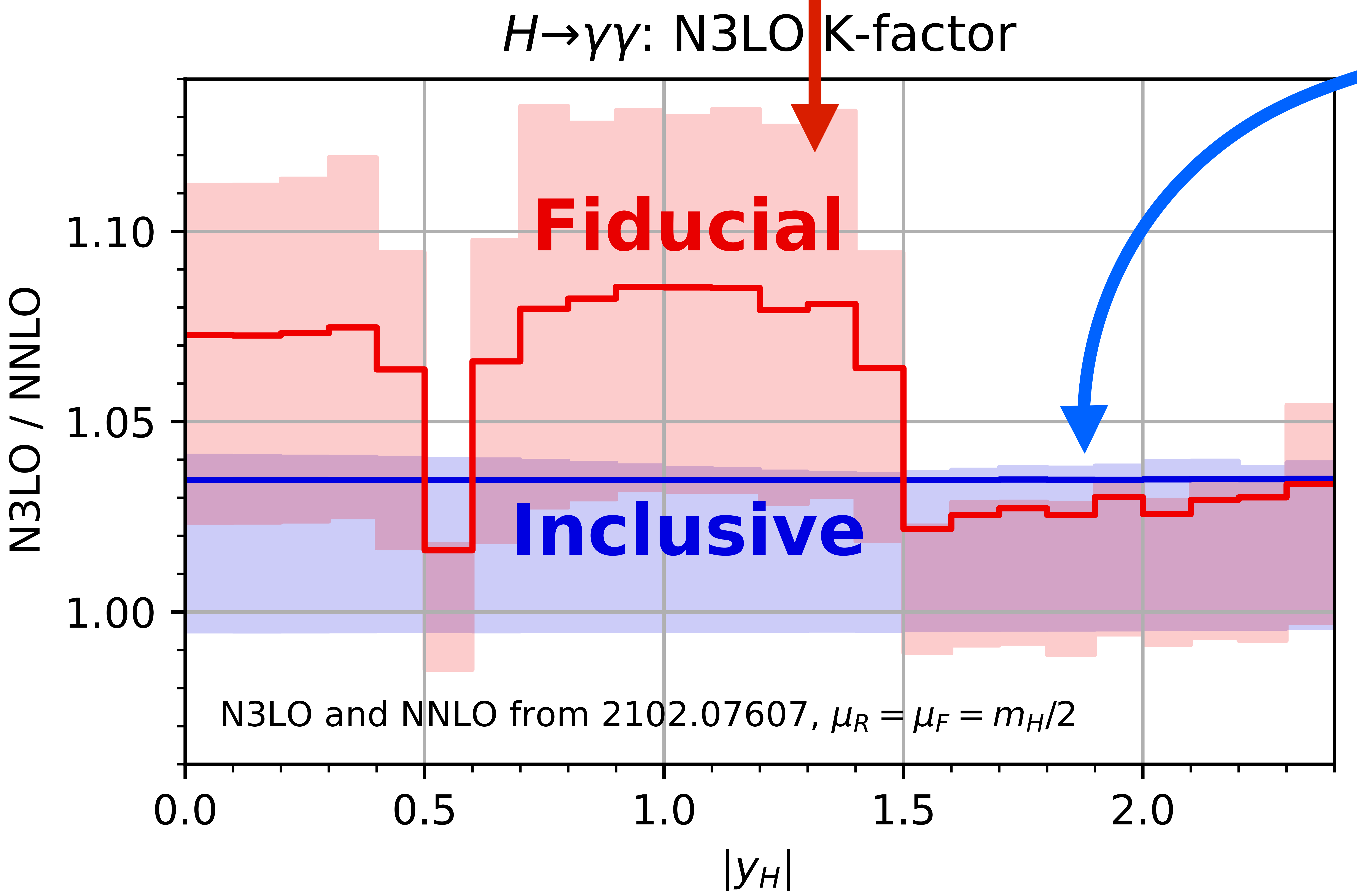
Recent surprise: H→γγ

inclusive N3LO σ uncertaities



Chen, Gehrmann, Glover, Huss, Mistlberger & Pelloni, 2102.07607

Recent surprise: H→γγ fiducial N3LO σ uncertainties ~2× greater than inclusive N3LO σ uncertaities

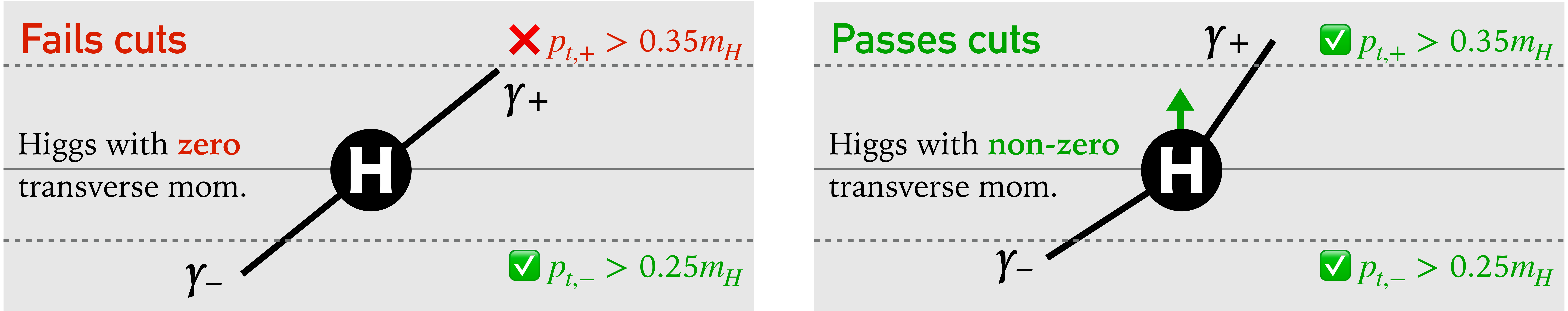


Chen, Gehrmann, Glover, Huss, Mistlberger & Pelloni, 2102.07607

"Gold standard" fiducial cross section gives much worse prediction

Why?
And can this be solved?

Standard $p_{t,\gamma}$ cuts → Higgs p_t dependence of acceptance

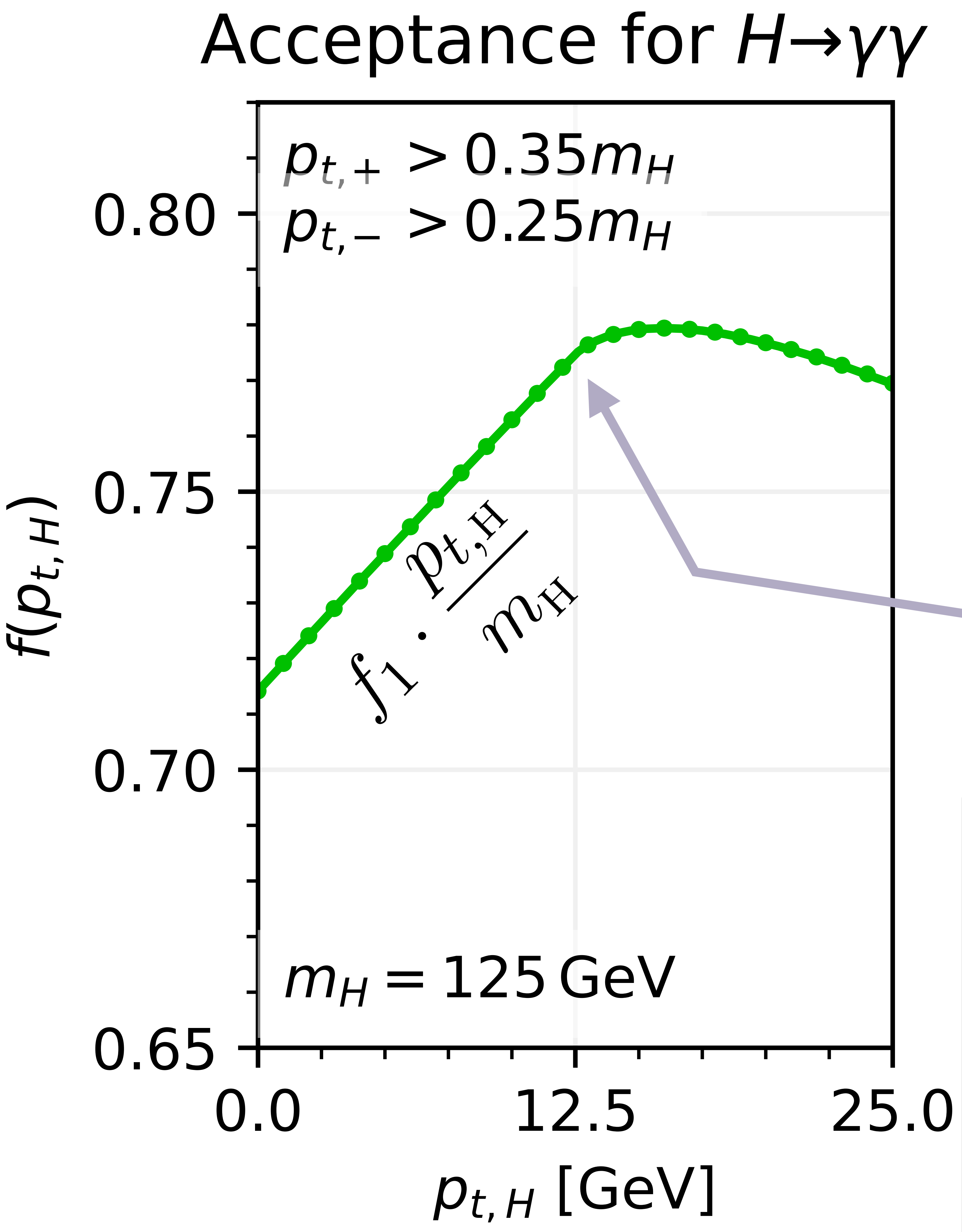


Numbers are for ATLAS H→ γγ p_t cuts, CMS cuts are similar

Expect acceptance to **increase with increasing $p_{t,\mathrm{H}}$**

$$p_{t,\pm}(p_{t,\mathrm{H}}, \theta, \phi) = \frac{m_\mathrm{H}}{2}\sin\theta \pm \frac{1}{2}p_{t,\mathrm{H}}|\cos\phi| + \frac{p_{t,\mathrm{H}}^2}{4m_\mathrm{H}}\left(\sin\theta\cos^2\phi + \csc\theta\sin^2\phi\right) + \mathcal{O}_3\,,$$

Linear p_{tH} dependence of H acceptance ≡ $f(p_{tH})$



$$f(p_{t,\mathrm{H}}) = f_0 + f_1 \cdot \frac{p_{t,\mathrm{H}}}{m_\mathrm{H}} + \mathcal{O}\left(\frac{p_{t,\mathrm{H}}^2}{m_\mathrm{H}^2}\right)$$

See e.g. Frixione & Ridolfi '97
Ebert & Tackmann '19
idem + Michel & Stewart '20
Alekhin et al '20

f_0 and f_1 are coefficients whose values depend on the cuts

effect of $p_{t,-}$ cut sets in at $0.1 m_\mathrm{H}$

$$\sigma_\mathrm{fid} = \sigma_\mathrm{tot}\left[f_0 + f_1 \sum_{n=1}^{\infty} (-1)^{n+1} \frac{(2n)!}{2(n!)} \left(\frac{2C_A\alpha_s}{\pi}\right)^n + \cdots\right]$$

GPS & Slade, 2106.08329

Growth $\propto n!$

Behaviour of perturbative series in various log approximations

Resummed results

$$\frac{\sigma_{\text{asym}} - f_0\sigma_{\text{inc}}}{\sigma_0 f_0} \simeq 0.15_{\alpha_s} - 0.29_{\alpha_s^2} + 0.71_{\alpha_s^3} - 2.39_{\alpha_s^4} + 10.31_{\alpha_s^5} + \ldots \simeq 0.06 \quad \text{@DL},$$

$$\simeq 0.15_{\alpha_s} - 0.23_{\alpha_s^2} + 0.44_{\alpha_s^3} - 1.15_{\alpha_s^4} + 3.86_{\alpha_s^5} + \ldots \simeq 0.06 \quad \text{@LL},$$

$$\simeq 0.18_{\alpha_s} - 0.15_{\alpha_s^2} + 0.29_{\alpha_s^3} + \ldots \simeq 0.10 \quad \text{@NNLL},$$

$$\simeq 0.18_{\alpha_s} - 0.15_{\alpha_s^2} + 0.31_{\alpha_s^3} + \ldots \simeq 0.12 \quad \text{@N3LL}.$$

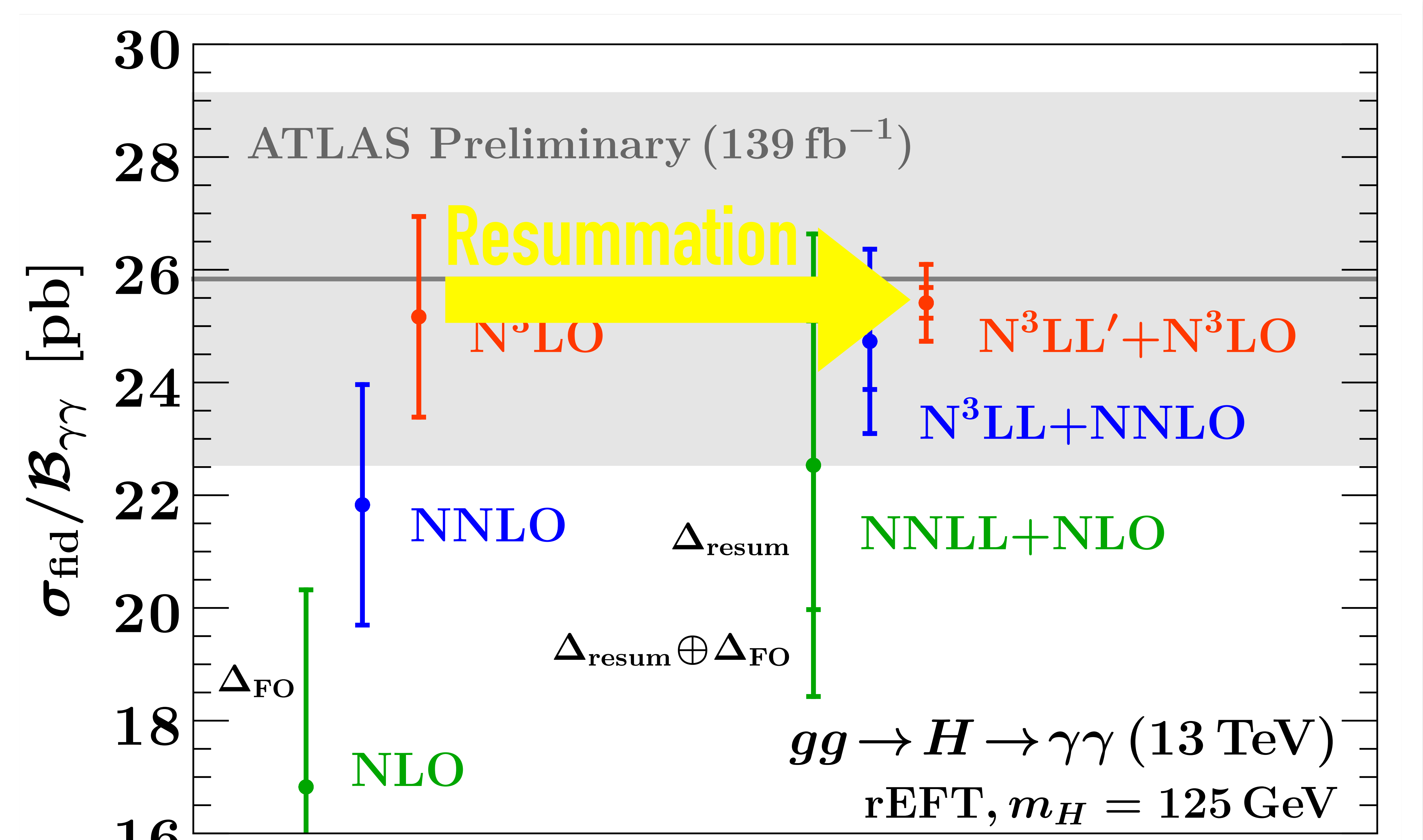
Thanks to Pier Monni & RadISH for supplying NN(N)LL distributions & expansions, $\mu = m_H/2$

- At DL & LL (DL+running coupling) **factorial divergence sets in from first orders**
- Poor behaviour of N3LL is qualitatively similar to that seen by Billis et al '21
- Theoretically similar to a power-suppressed ambiguity $\sim (\Lambda_{\text{QCD}}/m_{\text{H}})^{0.205}$ [inclusive cross sections expected to have Λ^2/m^2]

GPS & Slade, 2106.08329

Solution #1: only ever calculate σ_{fid} with help of p_{tH} resummation

- Billis, Dehnadi, Ebert, Michel & Tackmann, 2102.08039, argue you should evaluate the fiducial cross section only after resummation of the p_{tH} distribution.
- For legacy measurements, resummation is only viable solution
- Our view: not an ideal solution
  - Fiducial σ is a hard cross section and shouldn't need resummation
  - losing the ability to use fixed order on its own would be a big blow to the field (e.g. flexibility; robustness of seeing fixed-order & resummation agree)
  - sensitivity to variation of acceptance at low $p_{t,H}$ → complications (e.g. sensitivity to heavy-quark effects in resummation and PDFs — not consistently treated in any N3LL resummation today)



Billis, Dehnadi, Ebert, Michel & Tackmann, 2102.08039

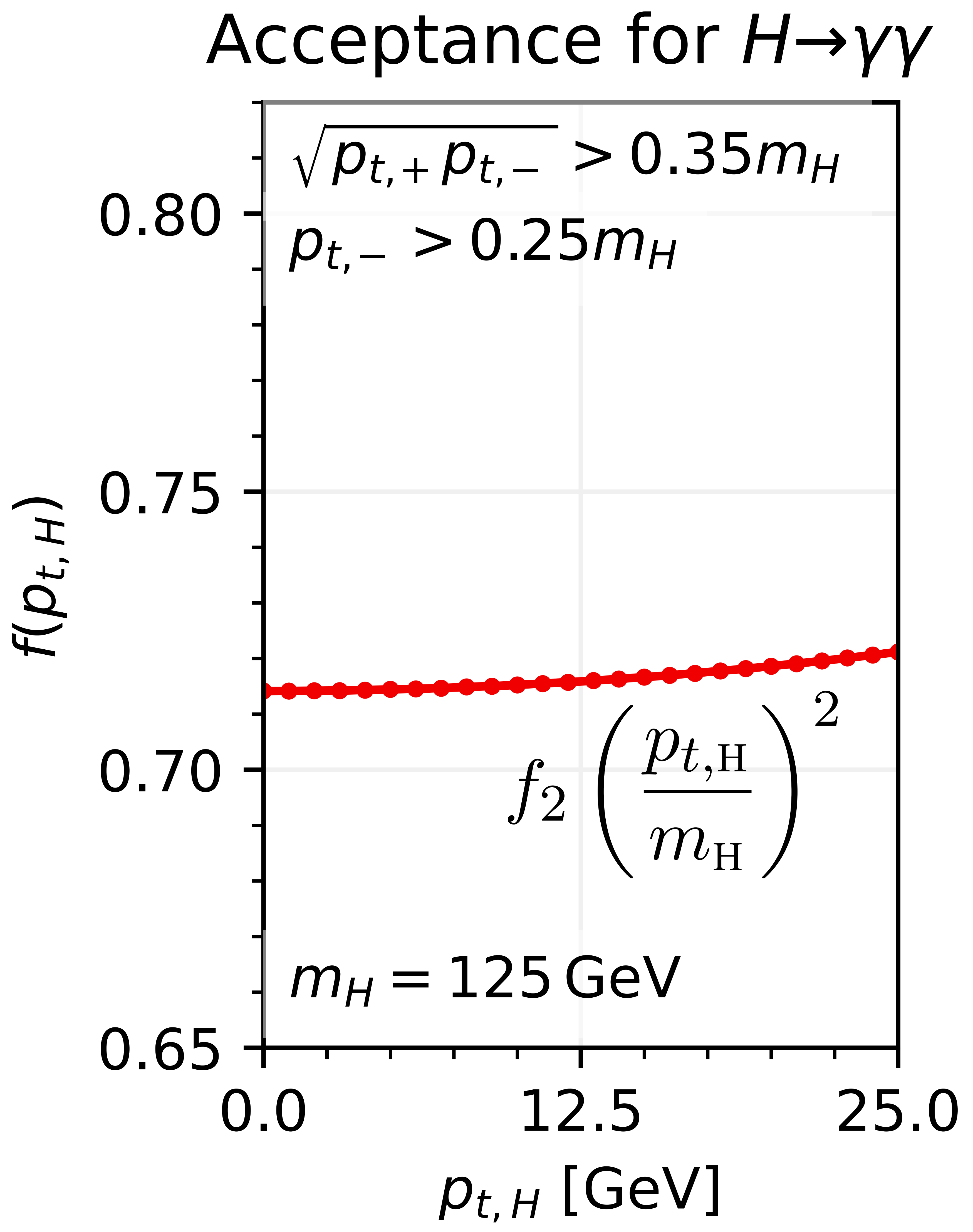
Solution #2a: for future measurements, make simple changes to the cuts

- Simplest option is to replace the cut on the leading photon with a cut on the product of the two photon p_t's
- E.g. $p_{t,\gamma+} \times p_{t,\gamma-} > (0.35 m_H)^2$ (and still keep softer photon cut $p_{t,\gamma-} > 0.25 m_H$)
- The product has no linear dependence on $p_{t,H}$

$$p_{t,\text{prod}}(p_{t,\text{H}}, \theta, \phi) = \sqrt{p_{t,+} p_{t,-}} = \frac{m_\text{H}}{2} \sin\theta + \frac{p_{t,\text{H}}^2}{4 m_\text{H}} \frac{\sin^2\phi - \cos^2\theta\cos^2\phi}{\sin\theta} + \mathcal{O}_4$$

[Several other options are possible, but this combines simplicity and good performance]

Replace cut on leading photon → cut on **product of photon p_t's**



$$f(p_{t,\mathrm{H}}) = f_0 + f_2 \left(\frac{p_{t,\mathrm{H}}}{m_\mathrm{H}}\right)^2 + \mathcal{O}\left(\frac{p_{t,\mathrm{H}}^2}{m_\mathrm{H}^2}\right)$$

linear → quadratic

$$\frac{(2n)!}{2(n!)}\left(\frac{2C_A\alpha_s}{\pi}\right)^n \rightarrow \frac{1}{4^n}\frac{(2n)!}{4(n!)}\left(\frac{2C_A\alpha_s}{\pi}\right)^n$$

Using product cuts dampens the factorial divergence

NB: the cut on the softer photon is still maintained

Behaviour of perturbative series with product cuts

$$\frac{\sigma_{\rm prod} - f_0\sigma_{\rm inc}}{\sigma_0 f_0} \simeq 0.005_{\alpha_s} - 0.002_{\alpha_s^2} + 0.002_{\alpha_s^3} - 0.001_{\alpha_s^4} + 0.001_{\alpha_s^5} + \ldots$$
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$$\simeq 0.005_{\alpha_s} + 0.002_{\alpha_s^2} - 0.001_{\alpha_s^3} + \ldots$$

Resummed results

$\simeq 0.003$ @DL,

$\simeq 0.003$ @LL,

$\simeq 0.005$ @NNLL,

$\simeq 0.006$ @N3LL.

Thanks to Pier Monni & RadISH for supplying NN(N)LL distributions & expansions, $\mu = m_H/2$

- Factorial growth of series strongly suppressed
- **N3LO truncation agrees well with all-order result**
- Per mil agreement between fixed-order and resummation **gives confidence that all is under control**

beyond the fixed-order formula

parton shower Monte Carlos

Take example of ATLAS boosted VH — stat (28%) ~ syst (24%)

ATLAS VH: 2008.02508,

Source of uncertainty		Avg. impact
Total		0.372
Statistical		0.283
Systematic		0.240
Experimental uncertainties		
Small-R jets		0.038
Large-R jets		0.133
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.007
Leptons		0.010
b-tagging	b-jets	0.016
	c-jets	0.011
	light-flavour jets	0.008
	extrapolation	0.004
Pile-up		0.001
Luminosity		0.013
Theoretical and modelling uncertainties		
Signal		0.038
Backgrounds		0.100
↪ Z + jets		0.048
↪ W + jets		0.058
↪ $t\bar{t}$		0.035
↪ Single top quark		0.027
↪ Diboson		0.032
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For large-R jets, the uncertainties in the energy and mass scales are […] as described in [81]

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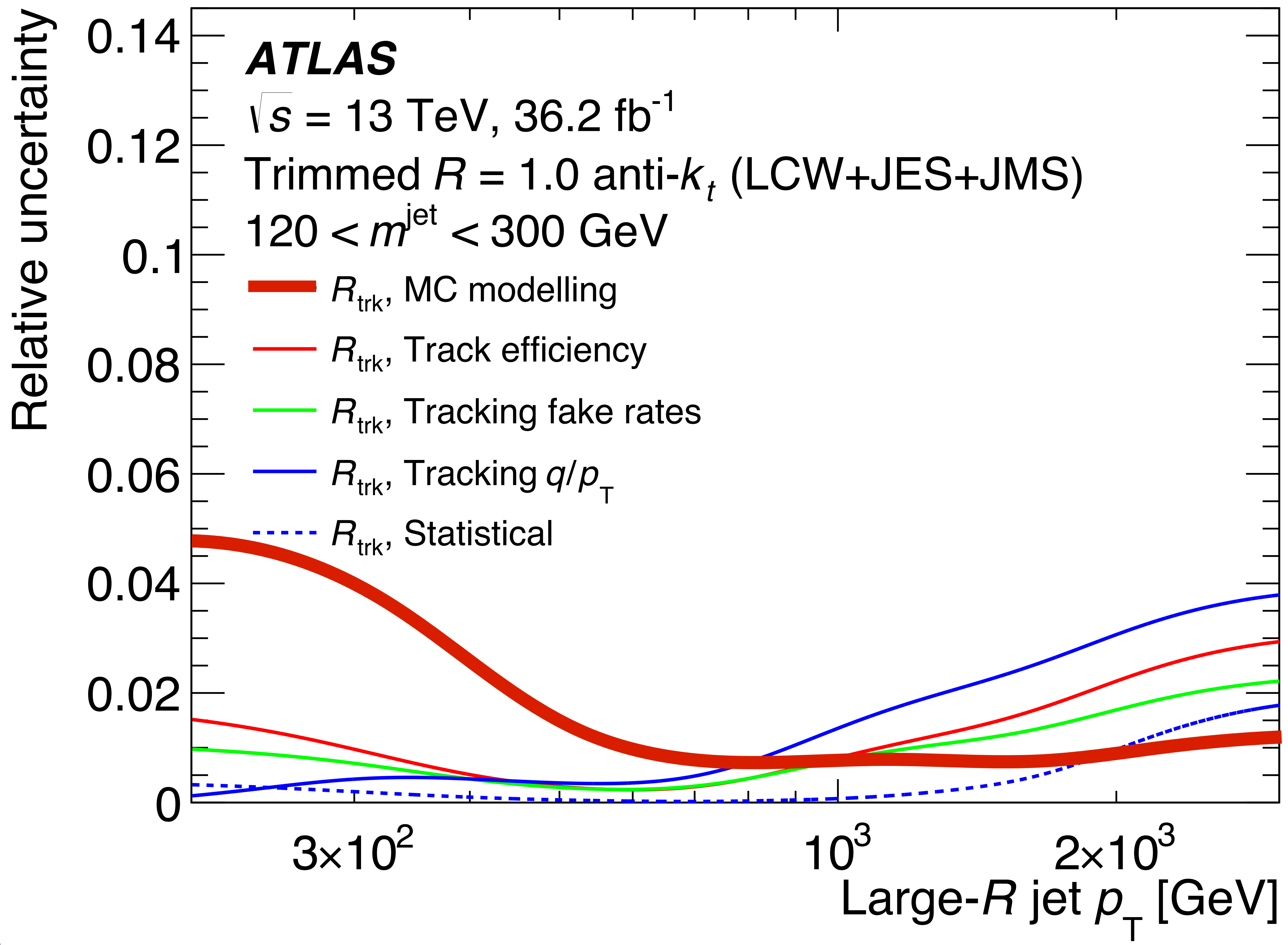

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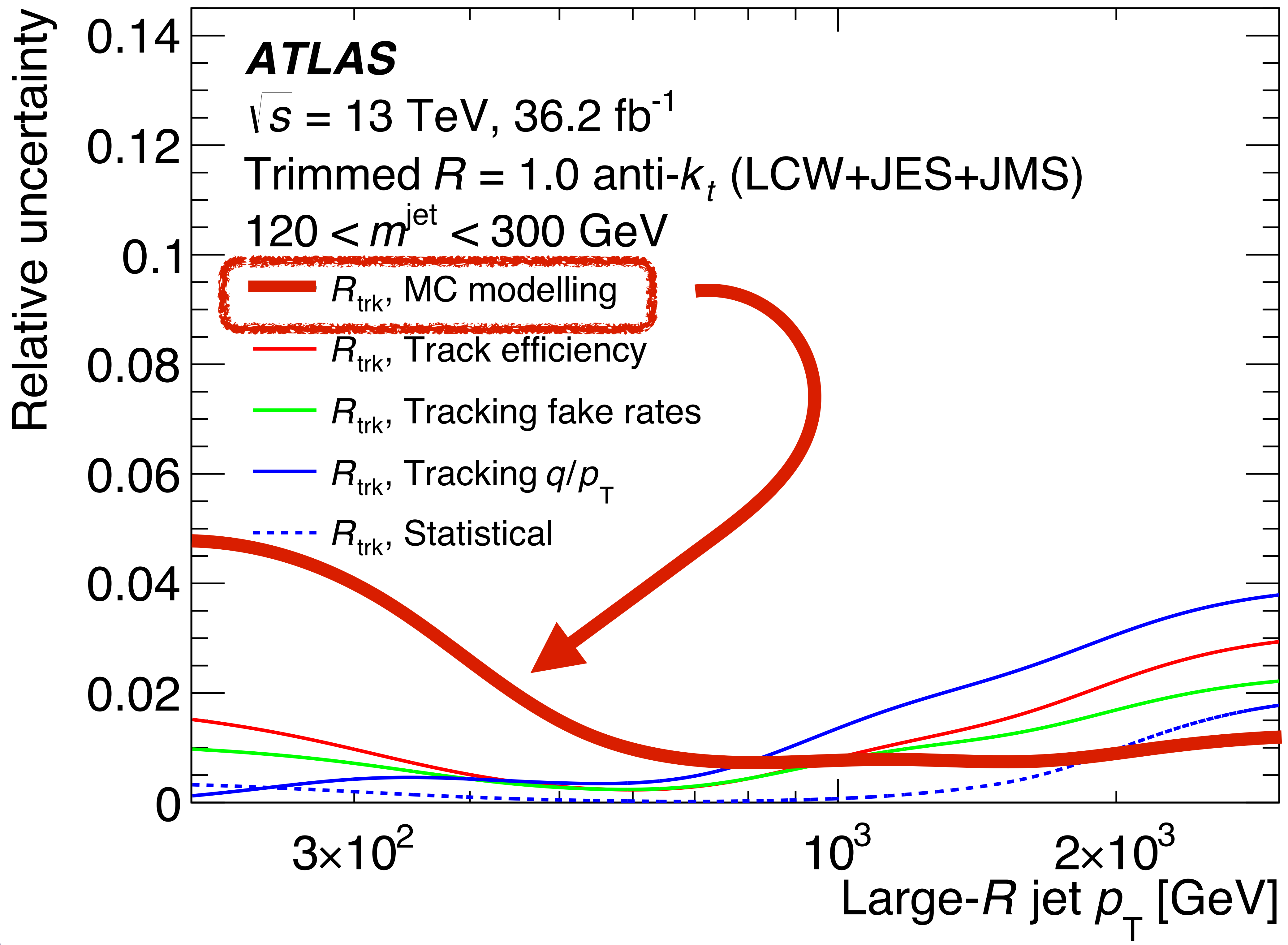
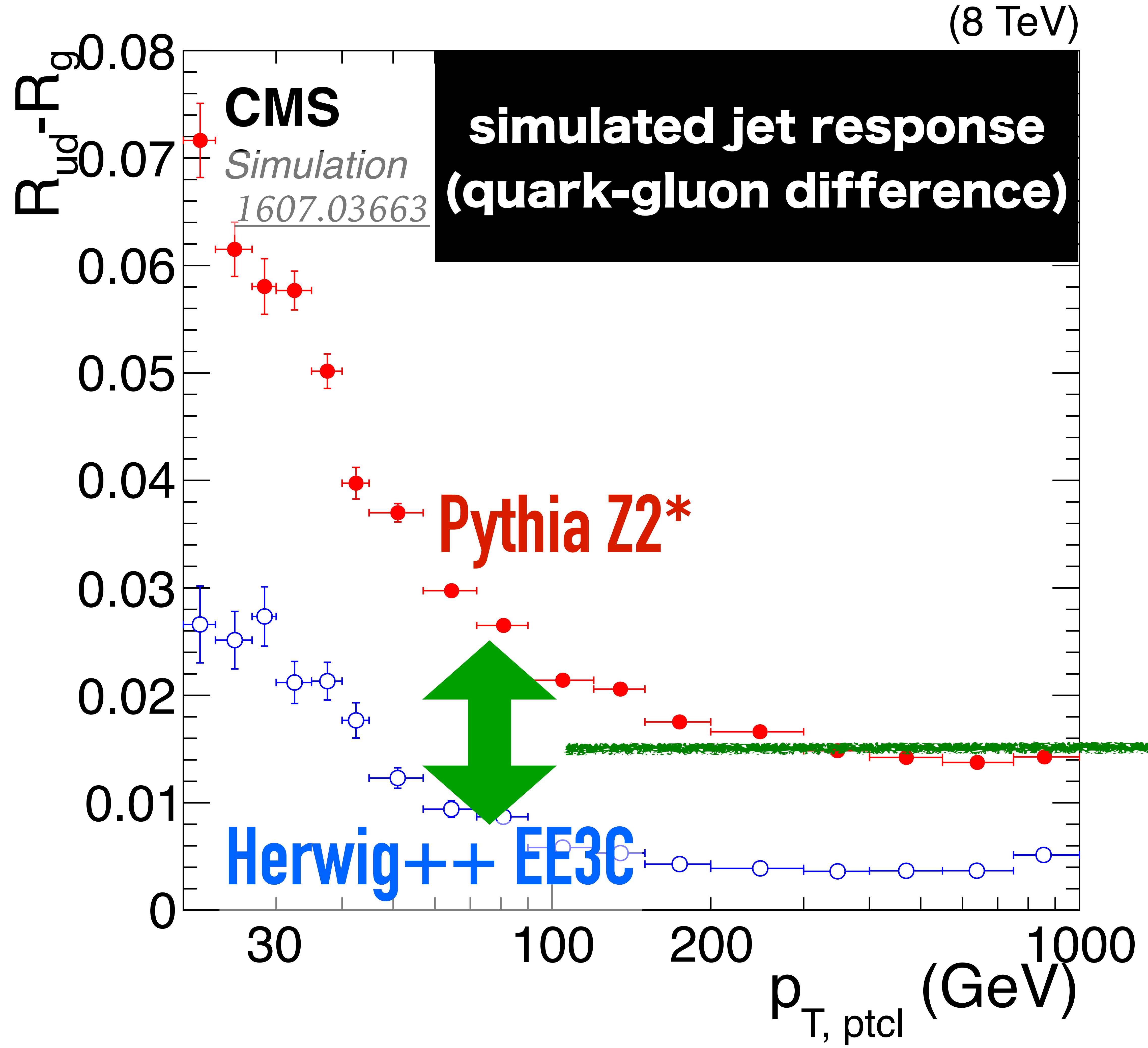
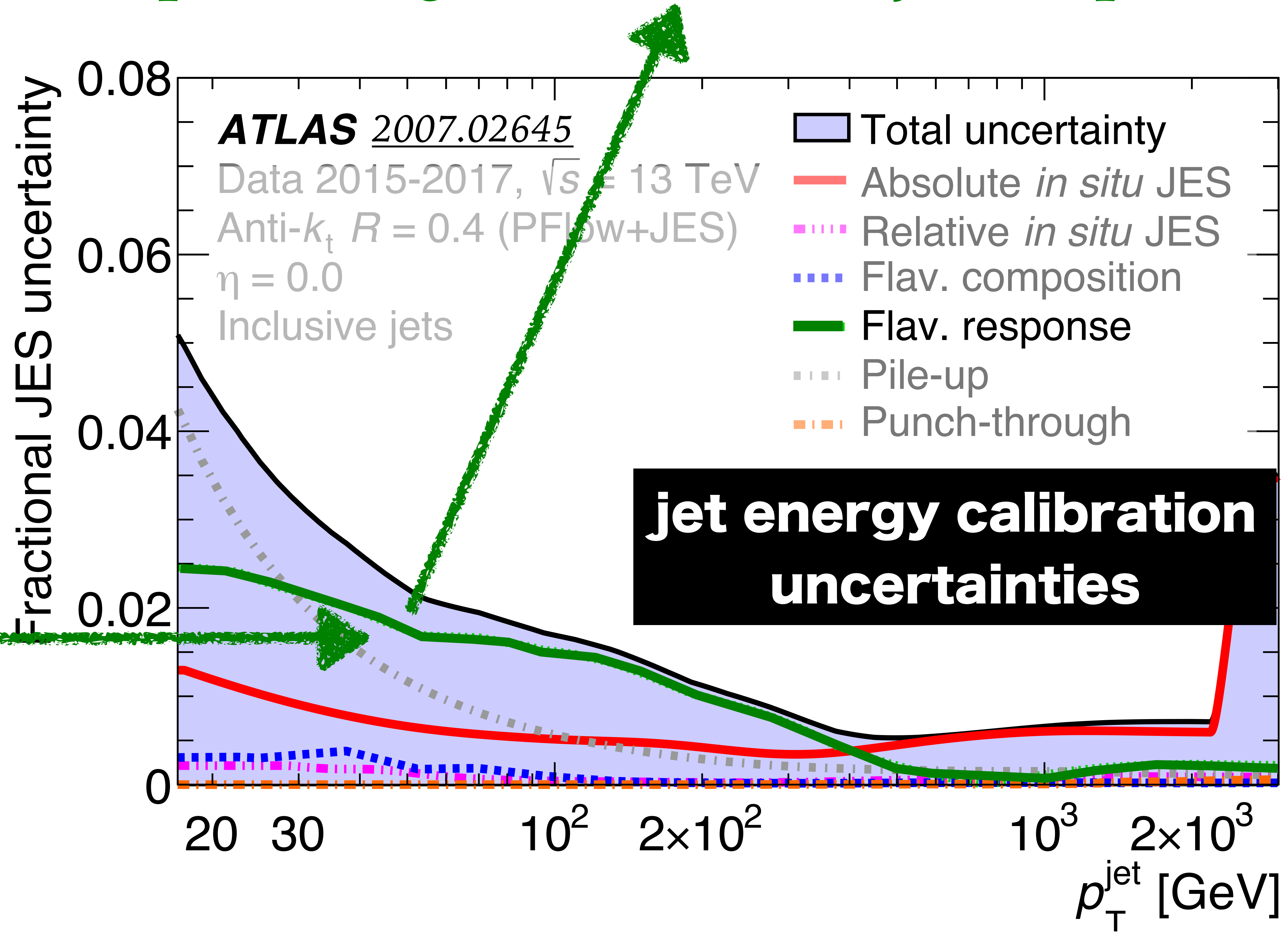


jet energy calibration affects ~1500 papers



Largest uncertainty source is poor understanding of [parton shower simulations of] quark v. gluon-induced jet responses



Resummation @N3LL, but parton showers only LL? Now evolving to NLL

Deductor	FHP	PanLocal	PanGlobal
$k_t\theta$ ("Λ") ordered	k_t ordered	$k_t\sqrt{\theta}$ ordered	k_t or $k_t\sqrt{\theta}$ ordered
Recoil	**Recoil**	**Recoil**	**Recoil**
$\perp$: local	$\perp$: global	$\perp$: local	$\perp$: global
$+$: local	$+$: local	$+$: local	$+$: local
$-$: global	$-$: global	$-$: local	$-$: local
Tests	**Tests**	**Tests**	**Tests**
analytical /numerical for thrust	analytical for thrust & multiplicity	numerical for many observables	numerical for many observables

Nagy & Soper
2011.04777 (+past decade)

Forshaw, Holguin & Plätzer
2003.06400

Dasgupta, Dreyer, Hamilton, Monni, GPS & Soyez 2002.11114
Hamilton, Medves, GPS, Scyboz, Soyez, 2011.10054
Karlberg, GPS, Scyboz, Verheyen, 2103.16526 + Hamilton 2111.01161

future colliders

Will e+e− colliders make precision easy?

Table 1.1. Relative statistical uncertainty on $\sigma_{\mathrm{HZ}} \times \mathrm{BR}(\mathrm{H} \to \mathrm{XX})$ and $\sigma_{\nu\bar{\nu}\mathrm{H}} \times \mathrm{BR}(\mathrm{H} \to \mathrm{XX})$, as expected from the FCC-ee data, obtained from a fast simulation of the CLD detector and consolidated with extrapolations from full simulations of similar linear-collider detectors (SiD and CLIC).

$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma\mathrm{BR})/\sigma\mathrm{BR}$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
$\mathrm{H} \to$ any	±0.5		±0.9	
$\mathrm{H} \to \mathrm{bb}$	±0.3	±3.1	±0.5	±0.9
$\mathrm{H} \to \mathrm{cc}$	±2.2		±6.5	±10
$\mathrm{H} \to \mathrm{gg}$	±1.9		±3.5	±4.5
$\mathrm{H} \to \mathrm{W^+W^-}$	±1.2		±2.6	±3.0
$\mathrm{H} \to \mathrm{ZZ}$	±4.4		±12	±10
$\mathrm{H} \to \tau\tau$	±0.9		±1.8	±8
$\mathrm{H} \to \gamma\gamma$	±9.0		±18	±22
$\mathrm{H} \to \mu^+\mu^-$	±19		±40	
$\mathrm{H} \to$ invisible	<0.3		<0.6	

Notes. All numbers indicate 68% CL intervals, except for the 95% CL sensitivity in the last line. The accuracies expected with 5 ab^{-1} at 240 GeV are given in the middle column, and those expected with 1.5 ab^{-1} at $\sqrt{s} = 365$ GeV are displayed in the last column.

- Up to $\sim \times 10$ reduction in uncertainties
- Interpreting 0.3% for $H \to b\bar{b}$ will require substantial improvements in parametric inputs
- Much of the statistics involves hadronic modes — how well will we be able to exploit them?
- Agreement between e^+e^- and LHC will be powerful validation of hadron colliders as precision machines

conclusions

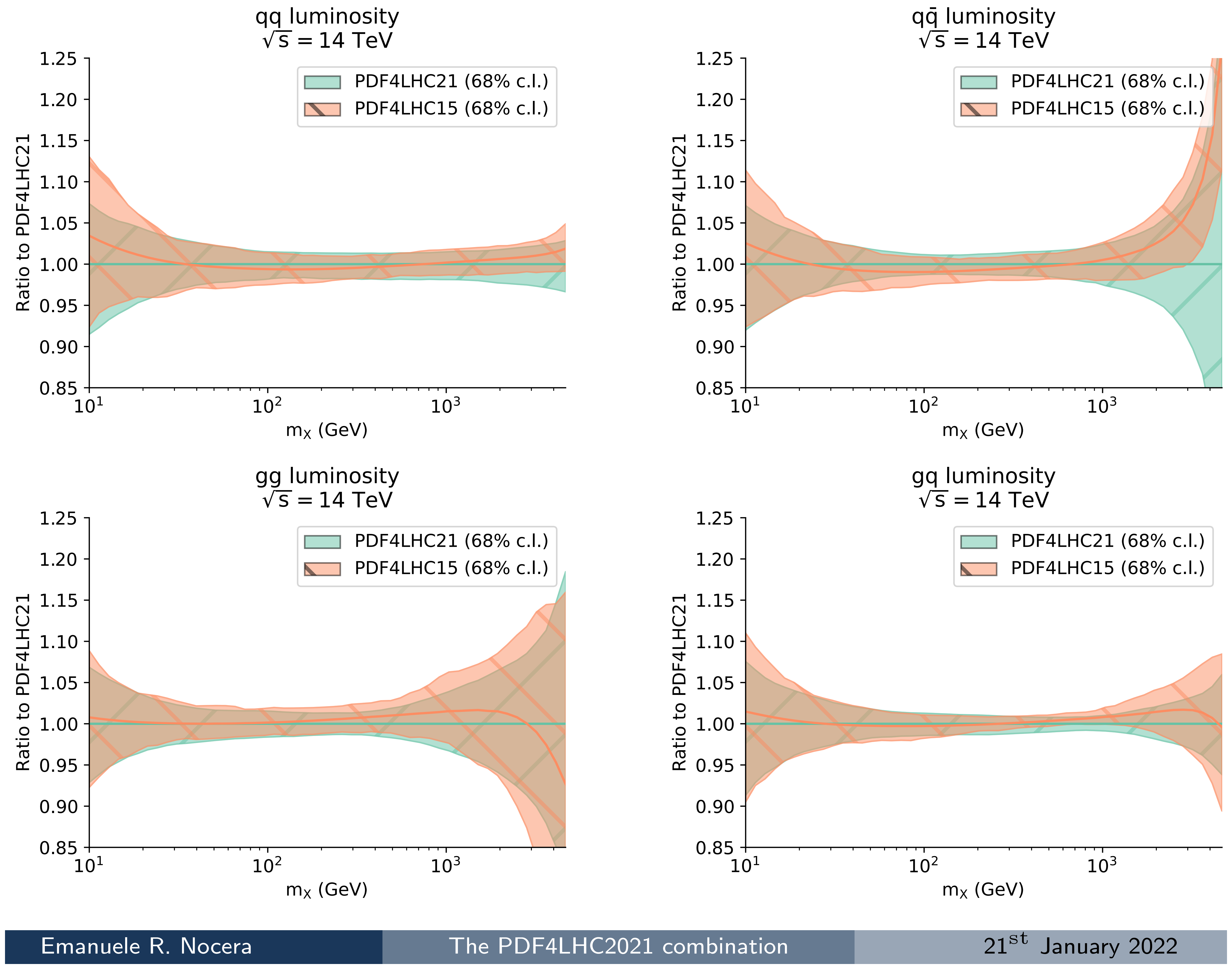
Conclusions

- Across much of Higgs physics, theory / MC uncertainties are among the dominant systematic uncertainties — addressing them will be key to benefitting from $\times 20$ statistics of the next 15 years.
- Perturbative calculations are making amazing strides
  → technically immensely challenging, and making remarkable progress
  → there are still conceptual surprises, e.g. impact of fiducial cuts
- Other aspects (parameters, PDFs, parton showers, non-perturbative contributions) force us to address conceptually complicated questions,
  → major progress on understanding structure of non-perturbative contributions
  → prospects for taking parton showers beyond "traditional" Leading Log accuracy

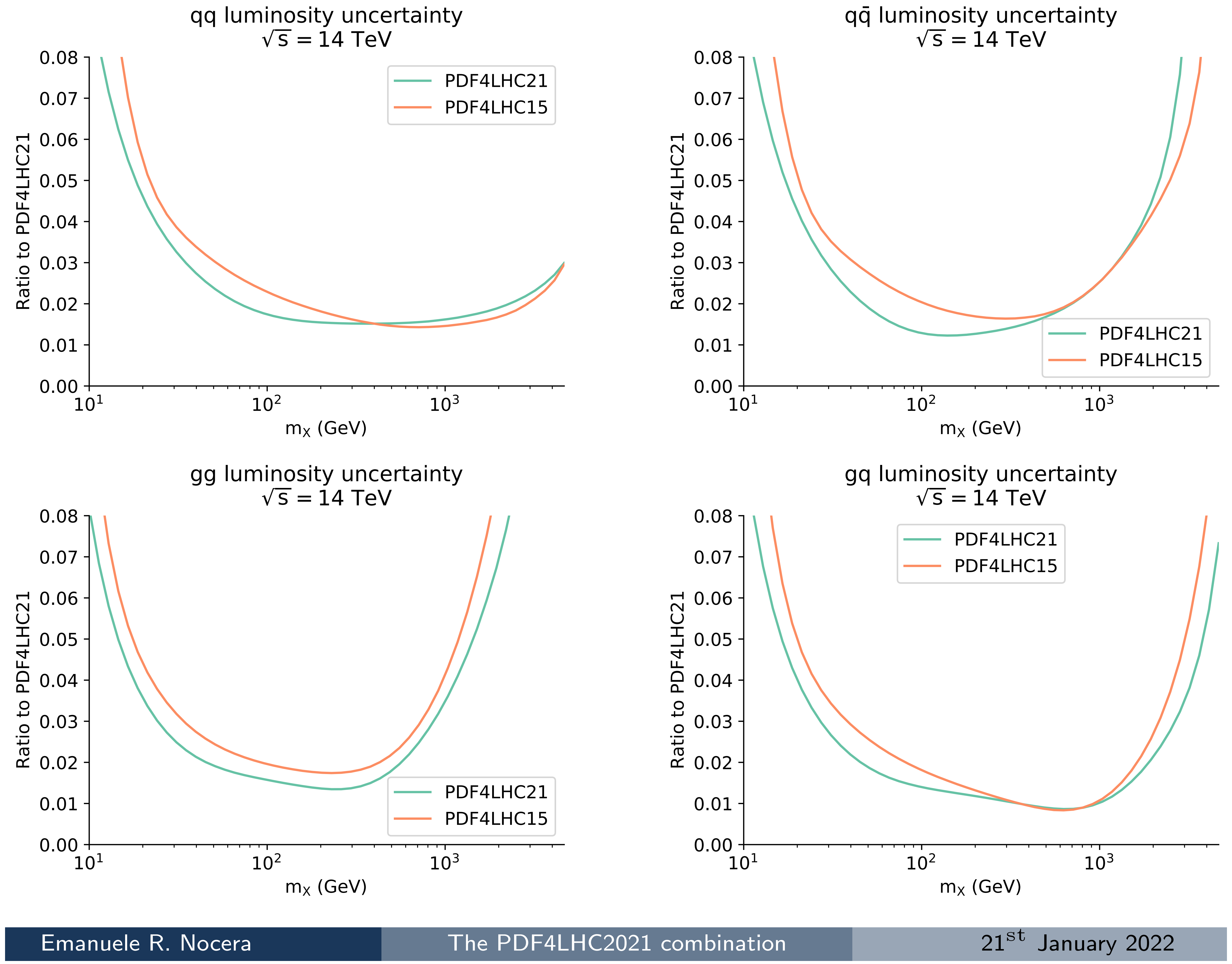
backup

PDF4LHC21 v. PDF4LHC15

partonic luminosities



luminosity uncertainties



perturbative series for fiducial cross sections

$$f(p_{t,\mathrm{H}}) = f_0 + f_1 \cdot \frac{p_{t,\mathrm{H}}}{m_\mathrm{H}} + \mathcal{O}\left(\frac{p_{t,\mathrm{H}}^2}{m_\mathrm{H}^2}\right)$$

Fiducial cross section depends on acceptance and Higgs p_t distribution

$$\sigma_{\text{fid}} = \int \frac{d\sigma}{dp_{t,\mathrm{H}}} f(p_{t,\mathrm{H}}) dp_{t,\mathrm{H}}$$

To understand qualitative perturbative behaviour consider simple (double-log) approx for p_t distribution

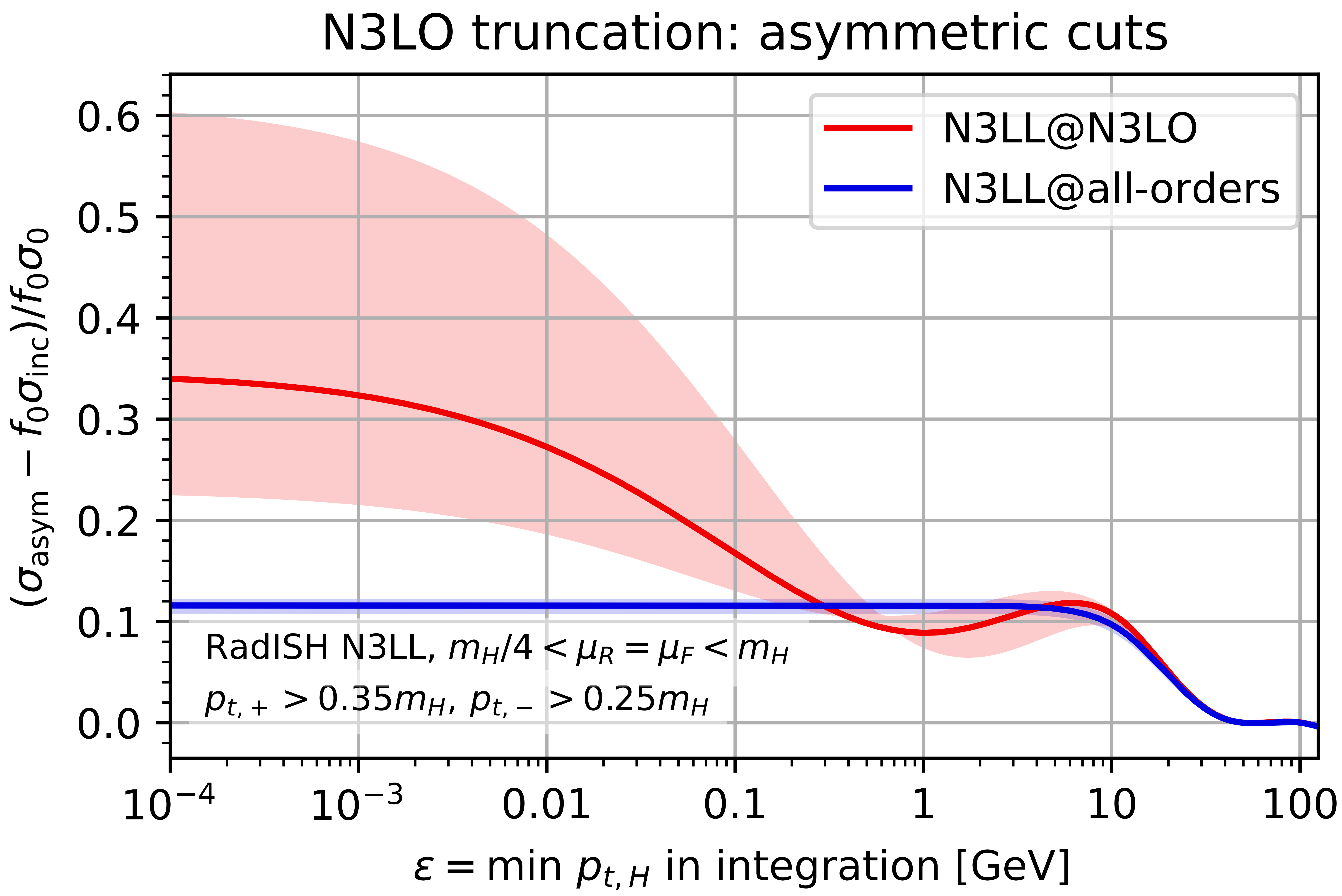
$$\frac{d\sigma^{\mathrm{DL}}}{dp_{t,\mathrm{H}}} = \frac{\sigma_{\text{tot}}}{p_{t,\mathrm{H}}} \sum_{n=1}^{\infty} (-1)^{n-1} \frac{2\log^{2n-1}\frac{m_\mathrm{H}}{2p_{t,\mathrm{H}}}}{(n-1)!} \left(\frac{2C_A\alpha_s}{\pi}\right)^n$$

Integrate to get result.
Observe pathological perturbative behaviour

$$\sigma_{\text{fid}} = \sigma_{\text{tot}} \left[f_0 + f_1 \sum_{n=1}^{\infty} (-1)^{n+1} \frac{(2n)!}{2(n!)} \left(\frac{2C_A\alpha_s}{\pi}\right)^n + \cdots \right]$$

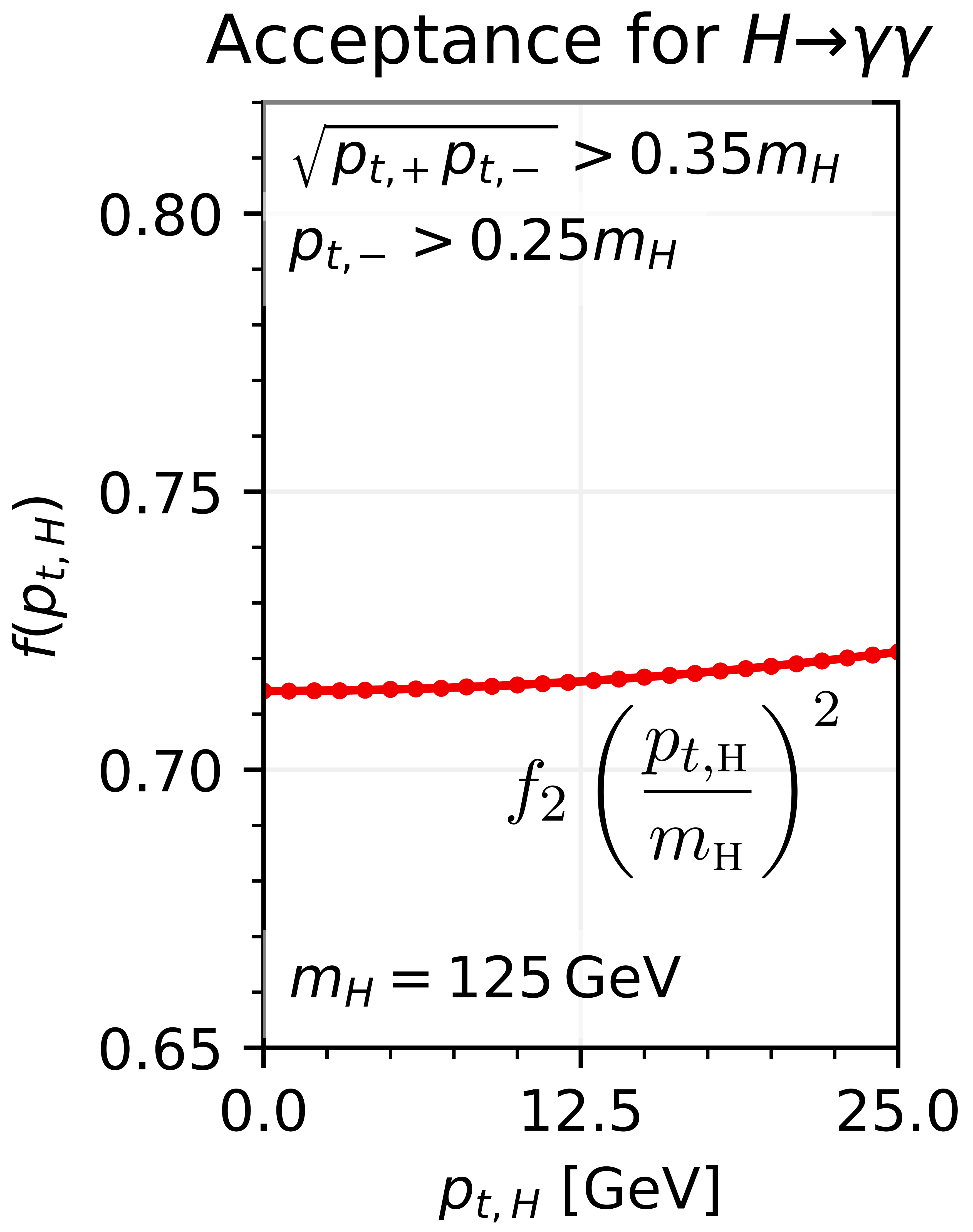
Growth $\propto n!$

Sensitivity to low Higgs p_t (and also scale bands): standard cuts



- fixed-order result very sensitive to minimum $p_{t,\mathrm{H}}$ value explored in phase-space integration
- only converges once you explore down to $p_{t,\mathrm{H}} \sim 1\,\mathrm{MeV}$
- i.e. extremely difficult to get reliable fixed-order result and once you have it, it is of dubious physical meaning

Replace cut on leading photon → cut on **product of photon p_t's**

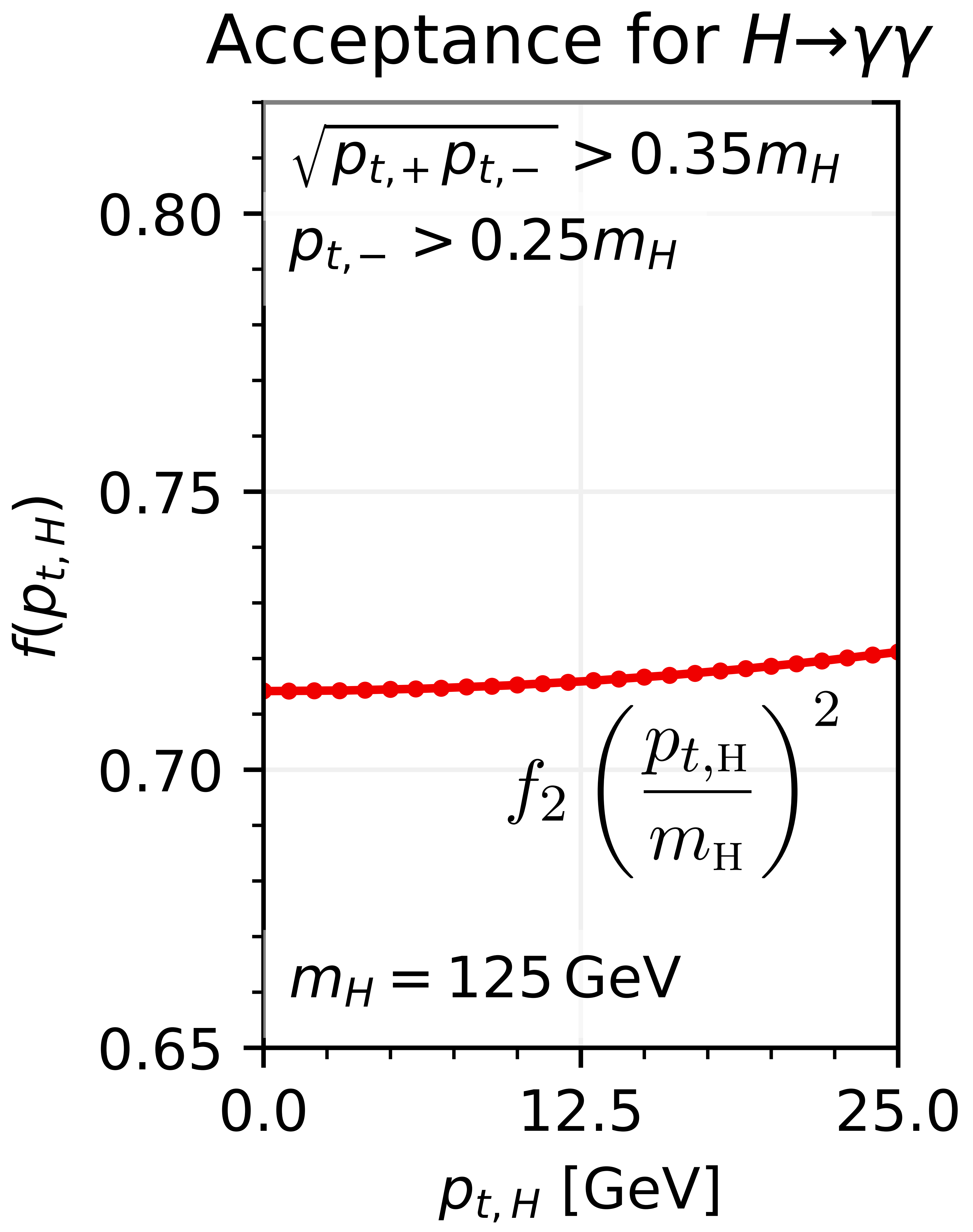


$$f(p_{t,H}) = f_0 + f_2\left(\frac{p_{t,H}}{m_H}\right)^2 + \mathcal{O}\left(\frac{p_{t,H}^2}{m_H^2}\right)$$

linear → quadratic

NB: the cut on the softer photon is still maintained

Replace cut on leading photon → cut on product of photon p_t's



$$f(p_{t,\mathrm{H}}) = f_0 + f_2\left(\frac{p_{t,\mathrm{H}}}{m_\mathrm{H}}\right)^2 + \mathcal{O}\left(\frac{p_{t,\mathrm{H}}^2}{m_\mathrm{H}^2}\right)$$

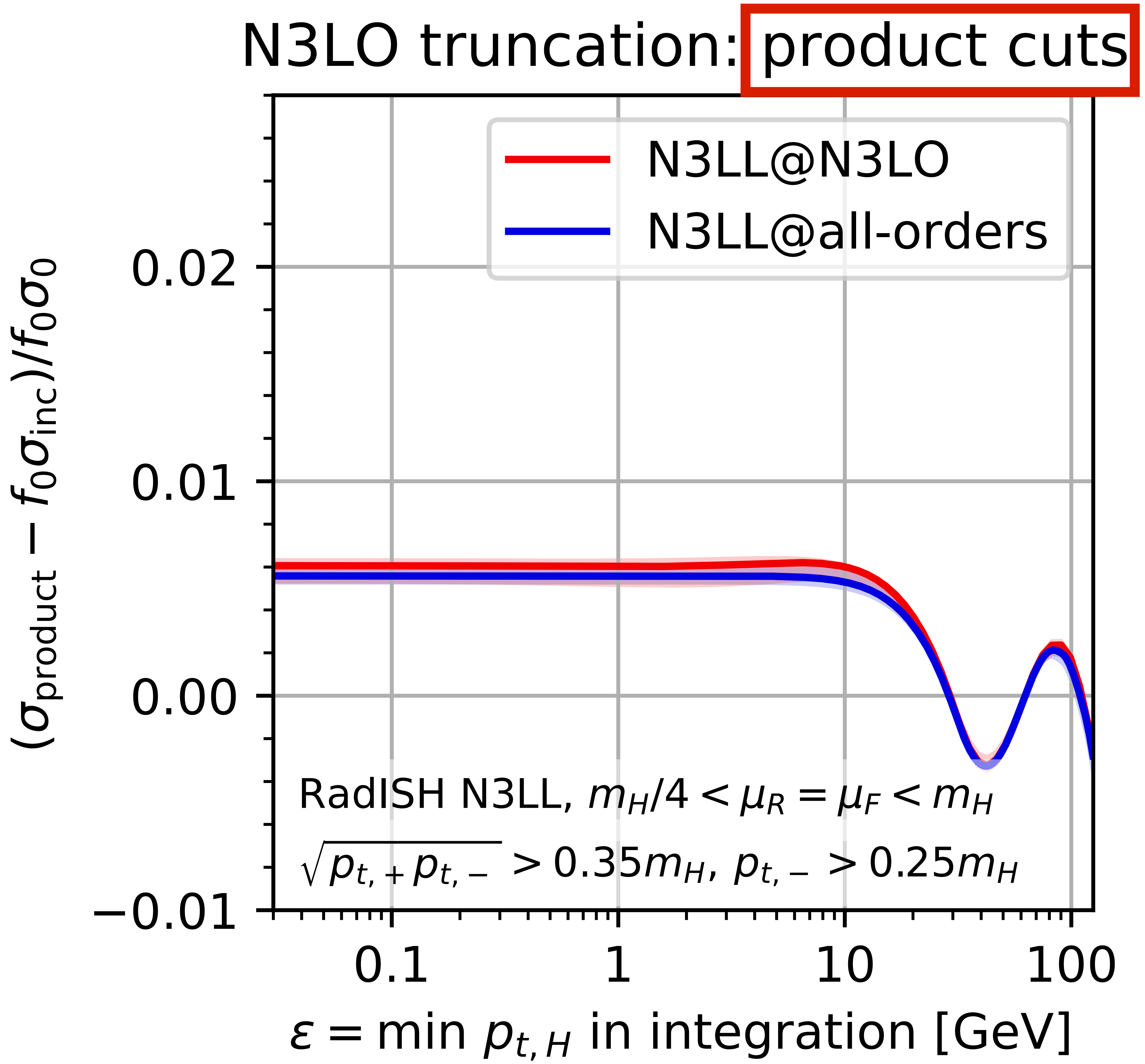
linear → quadratic

$$\frac{(2n)!}{2(n!)}\left(\frac{2C_A\alpha_s}{\pi}\right)^n \rightarrow \frac{1}{4^n}\frac{(2n)!}{4(n!)}\left(\frac{2C_A\alpha_s}{\pi}\right)^n$$

Using product cuts dampens the factorial divergence

NB: the cut on the softer photon is still maintained

fixed-order sensitivity to low p_{tH} is gone



- fixed-order becomes insensitive to $p_{t,\mathrm{H}}$ values below a few GeV
- overall size of (non-Born part of) fiducial acceptance corrections much smaller
- resummation and fixed order agree at per-mil level